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Visualizing the Impacts of Renewable Energy Growth in the U.S. Midcontinent

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ABSTRACT This paper presents the visualization approach for enhancing analyses of the ongoing Renewable Integration Impact (RIIA) Assessment by the Midcontinent Independent System Operator (MISO), and brings the following contributions. First, this paper details the customization of state-of-the-art, open-source visualization code to complement existing power system visualization tools and data analytic processes used in MISO. Second, this paper describes how MISO integrates this visualization tool within a novel and holistic process for studying renewable integration issues. This visualization tool provides additional insights for RIIA from multiple aspects with fine spatial-temporal granularity, including the comparison of thermal generation performance at different renewable integration scenarios, improved understanding of complex interactions between regions within MISO, the effects of transmission upgrades on curtailment reduction using optimization techniques, and the improved verification of MISO's simulation results. Lastly, we make the updated visualization code package publicly available.

INDEX TERMS Technology transfer, power system visualization, renewable integration.

I. INTRODUCTION

IN THE last decade, the amount of renewable energy integrated into the bulk electric power system in the United States has increased significantly, owing to various federal and state policies, continued reduction in capital costs, and public interests in zero-carbon generation resources. The Midcontinent Independent System Operator (MISO), which covers an area spanning all or part of 15 U.S. states and one Canadian province (Manitoba) (Fig. 1), also experienced a substantial growth of renewable energy within its footprint. MISO had approximately 634 terawatt-hours of annual energy production in 2018, with 7.8%, or 49.7 terawatt-hours, of energy produced by wind resources [1]. Solar resources only provided 0.6 terawatt-hours of energy in 2018. The most recent generator interconnection queue (as of December 2018) reflects that 42 GW of wind and 37 GW of solar projects are waiting to integrate into MISO market in coming years [2].

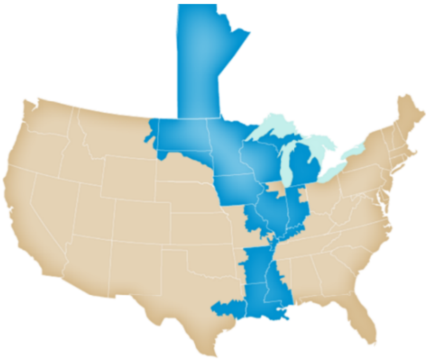

FIGURE 1. **MISO's footprint.**

To forecast continued growth of renewables, as well as to understand the impact of its increasing penetration to the bulk electric grid, studies to date have mostly relied on sophisticated power system simulation tools with high spatial-temporal resolution. These modeling tools produce complex data for further analyses, and the electric industry is ramping up endeavors to harmonize and visualize these large datasets for various reasons. First, most modeling or simulation tools display outputs in the format of spreadsheets or specific descriptive statistics. Further investigation into these modeling results requires significant time and effort. Although experienced researchers may be able to spot extreme output anomalies, they may miss the more subtle errors if simply looking at the raw output data. With visualizations of the modeling outputs, analysts can easily notice unusual patterns and any deviations from expected outcomes, which could be indicators of errors within the creation or execution of the model simulations. Second, from MISO's or any other Regional Transmission Organization's perspective, it is equally important to convey the results of these modeling analyses to various stakeholders, including state regulators, policymakers, and market participants, to facilitate conversations around the multifaceted complexity of integrating renewable energy into the bulk electric system. With visualizations of the modeling outputs, MISO can illustrate the multidimensional complexity of integrating renewable at different spatial-temporal granularity.

In this paper, MISO presents an ongoing effort to implement and customize Kaleidoscope [3], an open-source, state-of-the-art visualization tool originally developed by National Renewable Energy Laboratory (NREL), for MISO's Renewable Integration Impact Assessment (RIIA) study [4]. In the RIIA, MISO utilizes PLEXOS [5], a commercial power market production cost simulation tool to simulate renewable integration and power market dispatch at different renewable penetration levels. MISO then utilizes Kaleidoscope to visualize and analyze PLEXOS simulation outputs. These efforts of data visualization have helped MISO to better streamline internal workflow, as well as to inform external parties in the context of understanding the impact of renewable integration on the MISO electric system. Finally, MISO uses these visualizations to enhance multiple transmission planning processes, including the use of comparative maps, to illustrate the benefits of optimal transmission solutions.

MISO's efforts in data visualization contribute to power system analytics in the following ways. First and foremost, MISO has made the updated Kaleidoscope package publicly available. Any organization may adopt and customize this visualization tool to accommodate its choice of power market model, study scope, and to meet its analytics needs. Second, by applying and customizing Kaleidoscope to visualize market simulation outputs with different spatial-temporal resolutions, MISO demonstrates that this visualization effort is effective in helping various parties understand the complexity of incorporating renewable generation resources into the bulk electric system. To date, MISO has held two public workshops to present key findings of the RIIA study. A series of visualizations produced by Kaleidoscope shows how resource mix and power flow in the MISO footprint may evolve. These visualizations are intuitive and easy to understand for attendants who may not have in-depth knowledge of how electricity markets work.

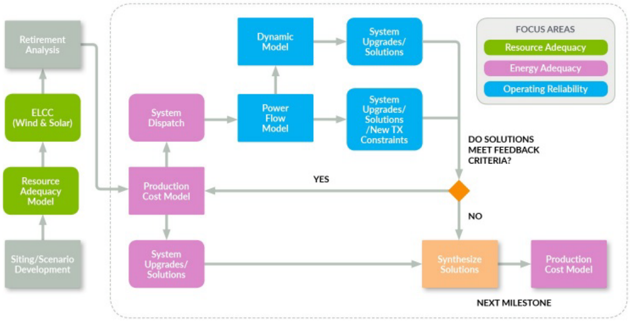

FIGURE 2. RIIA study framework and process.

The remainder of the paper is organized as follows: Section II provides background on MISO and RIIA, and discusses MISO's need for data visualization; Section III illustrates how MISO adopted and customized Kaleidoscope to visualize PLEXOS model outputs; Section IV demonstrates the implications of the customized Kaleidoscope tool; and Section V offers MISO's conclusion.

II. RENEWABLE INTEGRATION IMPACT ASSESSMENT AND MISO'S NEED FOR MODERN DATA VISUALIZATION TOOLS

A. MISO AND THE RENEWABLE INTEGRATION IMPACT ASSESSMENT (RIIA) STUDY

In 2016, MISO launched the RIIA study to identify integration complexities assuming 10% increments of renewable generation milestones. MISO defined a renewable generation milestone as the percentage of energy supplied by wind and solar resources to meet an assumed 2017 demand. The MISO RIIA team defined integration complexity as the ability of the system to meet a renewable integration milestone, while accounting for resource adequacy and ramping, transmission thermal, voltage, and frequency considerations. MISO then developed a novel study framework for RIIA that consists of three focus areas: Resource Adequacy (RA), Energy Adequacy (EA), and Operating Reliability (OR). Fig. 2 shows a high-level process flow diagram of the RIIA study framework [4]. The process is sequential unless a physical constraint (e.g., thermal violation) or modeling limitation (e.g., infeasibilities, increasing computational times) prevents the system from accommodating higher levels of renewables. A feedback loop is included to solve integration complexities within each focus area.

The RIIA study process begins with a siting process for wind and solar resources, including 100-meter utility-scale inland wind, single-axis tracking utility-scale solar photovoltaic (PV), and fixed-axis distributed-scale solar PV, based on renewable resource quality, active projects in the interconnection queue, and proximity to high voltage transmission. For distributed generation resources, additional criteria were also considered, e.g. areas with high-density populations, income ranges, and varying state policies. The study continues with an RA evaluation that assumes unconstrained transmission and neglects mechanically forced outage rates (FOR) for renewables. RA is a key component of MISO's planning process pursuant to reliability standards established by the North American Electric Reliability Corp. (NERC). The RA area in the context of RIIA framework focuses on quantifying the potential capacity contribution of wind and solar resources to comply with the one-day-in-10-years Loss of Load Expectation (LOLE) criteria.

By incorporating the capacity contribution assumptions of wind and solar from the RA focus area, the RIIA study proceeds to the EA focus area and develops resource generation and capacity scenarios for each milestone of renewable penetration. The RIIA team then utilizes PLEXOS [5] to simulate a security-constrained unit commitment (SCUC) and security-constrained economic dispatch (SCED) to ensure demand in every single hour is served cost-effectively. The RIIA team also conducts thorough examinations of modeling results, including hourly generation mix, operating reserves, system ramps, renewable curtailments, and transmission congestion.

Based on the results of hourly dispatch modeling from the. EA focus area, the RIIA team then selects snapshot points as representative samples of the system's most stressful operating points for transmission contingency analyses in the OR focus area. These representative stressful conditions include: (1) peak renewable output; (2) shoulder/light load with highest renewable penetration; and (3) peak load in MISO's footprint. The RIIA team performs steady-state powerflow and dynamics simulations for these stressful conditions to investigate any occurrence of thermal, voltage, and frequency response violations. The RIIA team repeats the above process until it solves all critical violations. Finally, a set of solutions (e.g., re-conducting an existing transmission line, adding new transmission elements, or re-dispatching committed generation resources) is identified to complete the analyses for a renewable penetration milestone. More information about the process can be found in the MISO Renewable Integration Impact Assessment workshop reports [6], [7].

B. MISO'S NEED FOR DATA VISUALIZATION

In order to support real-time operations, previous work on data visualization in power systems has primarily focused on the dynamic and stability aspects. Reference [8] introduced several techniques for visualizing transmission-related data for large-scale systems, and in [9] a framework was developed to identify transmission congestion to visualize the impact to the system with and without the congested element. References [10] and [11] focused on real-time monitoring of voltages, and in [12], a visualization tool based on contour geo-maps was developed to illustrate the effect of the largest credible contingency in the Eastern Interconnection on the system's frequency response. More recently, [13] applied several visualization techniques for co-optimized generation and transmission expansion planning applications to illustrate the temporal evolution of co-optimized investments.

MISO, to date, has relied on several commercial-grade and open-source data analytics and visualization tools for various analyses. These analytics tools fall into three main groups:

(1) Static contour/density maps. These maps are useful for illustrating/contrasting static snapshots of system conditions, e.g., differences in resource generations between an unconstrained transmission case and a constrained transmission case.

(2) Traditional statistical summaries using static stack bars, pie charts, and geographical maps. These illustrations are useful for showing interconnection queue projects, sitings from transmission planning futures (as found in the MISO Transmission Expansion Plan (MTEP) report), and market data (e.g., average locational marginal prices, congestion, and inter-change).

(3) Dynamic/animated geographical graphs. These figures are useful for demonstrating the effect of a large contingency event on the system reliability, e.g., frequency response.

During the RIIA work, MISO has found that the complex task of harmonizing the findings of three interdependent focus areas and finalizing a renewable penetration milestone requires additional data analytic and visualization tools to connect multi-dimensional, spatial-temporal data from three focus areas at different time scales. For example, the delivery of wind and solar generation to the load depends on transmission availability. Hence, demonstrating wind and solar generation from dispatch modeling results should not be illustrated as stand-alone bar charts, but need to be accompanied with transmission constraint conditions (which is contingent on voltages and frequency limits). The RIIA team has also found that a single static map limits the understanding of how system conditions change temporally under different renewable production scenarios, and deemed it necessary to develop or adopt visualization tools to produce time-lapse animations to facilitate the study.

III. ADOPTION AND CUSTOMIZATION OF NREL'S KALEIDOSCOPE FOR MISO ANALYTICS WORKS

NREL developed Kaleidoscope [3] specifically for the Eastern Renewable Generation Integration Study (ERGIS) [14] to visualize the sub-hourly generation dispatch and inter-regional powerflows under 10%, 20% and 30% renewable penetration levels in the Eastern Interconnection. NREL's Kaleidoscope is an R package developed to visualize the large ERGIS spatial-temporal production-cost data in a single framework. Since MISO participated in ERGIS, the RIIA team found the Kaleidoscope tool to be a good candidate to fulfill MISO's additional needs for data visualization. Whereas NREL has successfully applied Kaleidoscope to other related renewable integration studies [14]–[17], the RIIA team needed to customize the code to suit the needs of MISO and the RIIA study.

Kaleidoscope leverages the concept of multiple coordinated views that provide distinct views, or distinct visual representations, of production cost data. North and Shneiderman [18] have shown that multiple coordinated views can improve users' discovery of unknown relationships in complex data. Kaleidoscope provides three principal views: a geographic diagram illustrating the dispatch of generation by unit and fuel type; a chord diagram providing the magnitude and direction of the net interchange between regions; and dispatch charts showing an aggregated view of the fuel mix for each scenario. The prior Kaleidoscope studies have duplicated these views for each scenario under investigation.

The geographic diagram illustrates the study region on a map and shows the output of individual generators and net interchange between regions as directional arcs. The diagram represents generators as circular glyphs, plotted at each generator's location, colored by fuel type, and the area of each glyph sized as a linear function of each generator's output at the given timestep. The generation glyphs are semi-transparent to accommodate over-plotting and providing a density visualization of the generation. The glyphs are sorted by radius, plotting smaller glyphs on larger glyphs to make over-plotted areas easier to read. A static frame visualizes the geographic distribution of generation by fuel type. When animated, the cycling and ramping events become visible. The diagram represents net interchange with directed arcs, providing a qualitative view of the direction and magnitude of regional powerflow.

The chord diagrams provide a quantitative view of that powerflow, allowing users to measure the amount of interchange between regions or zones. Chord diagrams present a circular layout that shows directed relationships between chord intervals [19]. Each chord interval along the circumference represents the net interchange of a geographic region. Directed ribbons, sized proportionally to the flow, represent the constituent imports and exports of that interchange. The magnitude of flow between regions is legible from these plots. We have also found these plots to be particularly useful in comparing the net interchange differences between scenarios.

To extend the existing capabilities of Kaleidoscope to fit MISO's electric system terminology as well as to fulfill RIIA analyses objectives, the MISO RIIA team made three key efforts to adapt and customize the original NREL Kaleidoscope tool, including:

(1) Customization of the existing functions in the original NREL Kaleidoscope package for the MISO system. In particular, MISO made the following modifications/developments:

- Modify all relevant codes to fit Kaleidoscope into MISO topology and terminology
- Replace all map layers to reflect MISO's existing footprint

MISO also keeps the names of the original functions to facilitate the transfer of the modifications back to the original source code.

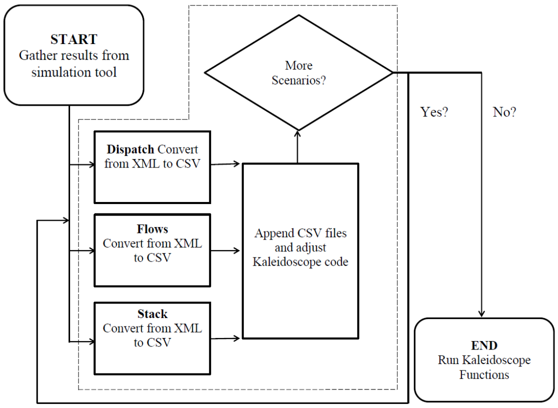

FIGURE 3. **Data processing framework.**

(2) To streamline the process of creating individual Portable Network Graphics (PNG), MISO created a graphical user interface (GUI) for users to enter their choices of input and output. The addition of a GUI eliminates the need to change the underlying code manually should users want to make any customized modification. Furthermore, the GUI allows for the selection of a single scenario or a comparative map showing multiple scenarios. All static files can be called from the GUI (shapefile containing geographical information, e.g., state/region borders, latitude/longitude information for each region or sub-region, list of generators with corresponding fuel type).

(3) MISO developed a supporting Python code to take the data output from PLEXOS and converted it into a form that would work with the given Kaleidoscope functions. The code extracts the solution file from PLEXOS and converts it into a CSV format suitable for Kaleidoscope. This feature removes the need for post-processing results, which also reduces the possibility of introducing errors in the process.

The MISO-updated and customized Kaleidoscope is available in [20]. Fig. 3 illustrates the process that MISO implements to customize Kaleidoscope. MISO has also developed a separate program to automate the sub-tasks (circumscribed by the dashed line) during the Kaleidoscope application.

IV. IMPLICATIONS OF KALEIDOSCOPE

A key motivation for adopting and customizing Kaleidoscope is to harmonize multi-dimensional, spatial-temporal data from three intertwined RIIA focus areas and to finalize renewable penetration milestone analyses in a much more efficient way. This section illustrates the implications of MISO's customized Kaleidoscope tool in the context of RIIA.

A. VISUALIZATION OF THE MISO SYSTEM UNDER DIFFERENT RENEWABLE INTEGRATION MILESTONES

In order to visualize how the MISO system transitions with an increasing penetration of renewable energy, in the RIIA study MISO uses Kaleidoscope to produce a series of static maps containing side-by-side comparisons of key results from PLEXOS hourly production cost simulations as shown

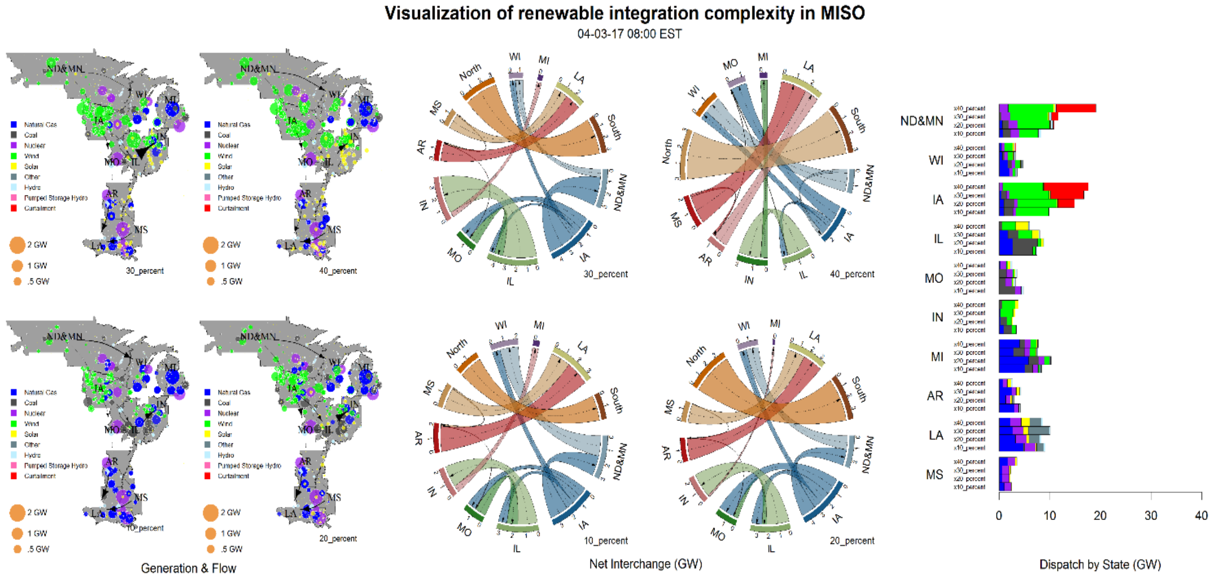

FIGURE 4. **Visualizing renewable integration in MISO (hour with high wind).**

in Fig. 4 (see the Appendix for Fig. 4 in full resolution). This example shows a representative high wind production hour, 8:00 a.m. on April 3, 2017, for 10% to 40% renewable penetration milestones respectively.

The left pane of Fig. 4 illustrates the dispatch of individual generation resources by fuel types and their location across the MISO footprint. Color-coded fuel types and varying bubble sizes illustrate the amount of generation output from each generation resource. To improve the visualization, fuel types are grouped to higher level roll-ups as: (1) the ''Natural Gas'' category, which includes combustion turbine-gas, steam-gas, IGCC, and combined cycle gas); and (2) the ''Other'' category, which includes all generation units that are not wind, solar, nuclear, coal, natural gas, or pumped storage hydro with capacities less than 50 MW. Black arrows demonstrate power flows between MISO local zones (the thicker the line, the larger the power flow), providing a qualitative, relative representation of the interchange between zones.

The center pane of Fig. 4 uses chord diagrams to represent the total interchange of energy between the MISO local resource zones (LRZs). State abbreviations show the approximation to MISO local resource zones as following: ''MN&ND'' for LRZ-1 (which also includes small portions of South Dakota and Montana); ''WI'' for LRZ-2 (which also includes Michigan's Upper Peninsula region); ''IA'' for LRZ-3; ''IL'' for LRZ-4; ''MO'' for LRZ-5; ''IN'' for LRZ-6; ''MI'' for LRZ-7; ''AR'' for LRZ-8; ''LA'' for LRZ-9 (including a small portion of East Texas); and ''MS'' for LRZ-10. Each LRZ or region is represented as an arc on the circle, with the width the arc reflecting the total interchange for the region. The width of the ribbon between regions corresponds to the magnitude of flow in megawatt units whereas the direction of the arrow in the ribbon shows the direction of flow. Similarly, the color the ribbon is dictated by the origin of the flow. For example, at the 10% integration level, the total interchange in Illinois, represented by the width of the light green arc, is 5 GW, driven by 3.5 GW of exports to Indiana and a total of 1.5 GW of imports from Iowa, North Dakota and Minnesota. These diagrams provide an abstract but quantitative representation of the zonal interchange.

Lastly, the right pane of Fig. 4 illustrates the quantity of total generation by fuel type and by zone in the given hour. The same color scheme is used for the horizontal stacked bars as in the generation bubbles in the left pane map. A new category represented by red bars is also included in the stack to capture the geographical breakdown of renewable curtailments.

Figure 4 contains a rich amount of information condensed into one single figure for ease of understanding and comparison. When the three panes are viewed together, one can easily see how the MISO system changes across different renewable penetration milestones. For instance, by comparing the 40% milestone with 10% scenario, one can observe that wind generation increases sharply in the 40% milestone, mostly from additional wind generation in Iowa in this sample hour (more green bubbles appear). The increases in Iowa wind production result in a notable change in powerflow out of Iowa, as net interchange increases from 3 GW in the 10% milestone to near 3.5 GW in the 40% milestone (see the center of Fig. 4). The horizontally stacked bars on the right side further provide direct visualization of wind generation and curtailment at this hour. One can find that, given the existing system transmission constraints, a notable amount of renewable energy is being curtailed due to inability of the system to deliver zero-marginal cost generation. When the system is unable to deliver low-cost generation, the model needs to

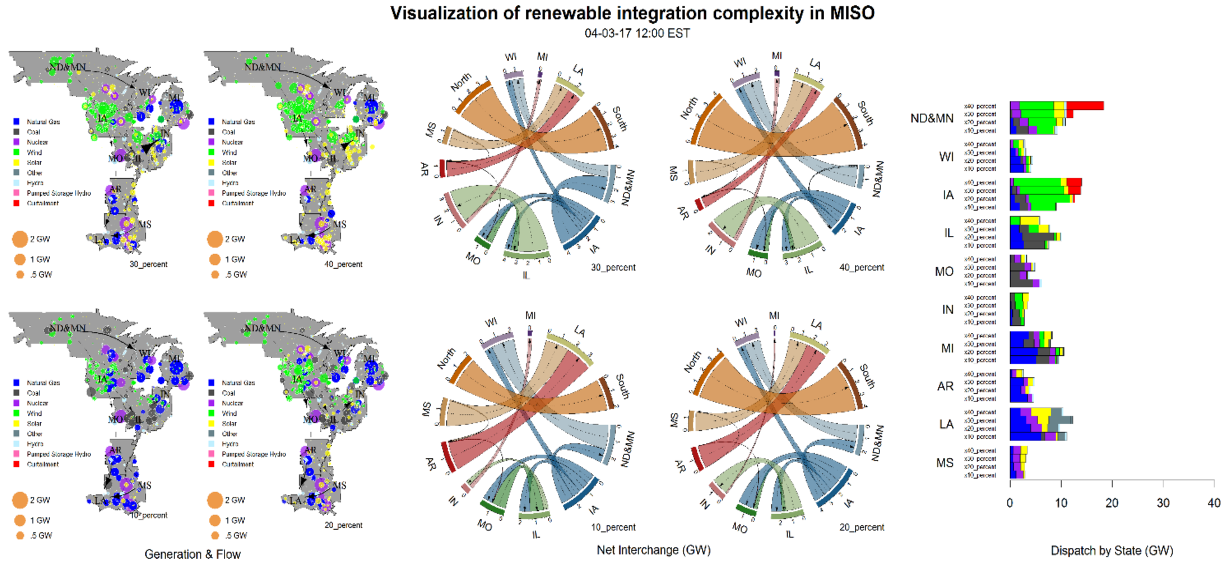

FIGURE 5. **Visualizing renewable integration in MISO (hour with high solar).**

commit and dispatch higher-cost generation resources located near the population centers in order to serve load.

A static comparative graph like Fig. 4 is useful to understand and compare system conditions between different renewable penetration milestones in the same time snapshot. On the other hand, combining multiple static figures allows the generation of a time-lapsed animation to illustrate how the MISO system changes over time. The Appendix includes an animation spanning the 24-hour period of April 3, 2017, to illustrate hourly changes in such areas as renewable production, ramping in thermal units, and powerflows (See Animation_Comparative_April_3rd in the Appendix). For instance, in terms of renewable production, the animation provides a direct visualization of the sunrise and sunset, as solar generation appears around 7 a.m. and disappears by 7 p.m., whereas wind tends to blow consistently. When the sun appears or disappears, the changes in powerflow (as shown in the center pane) are also notable.

B. ILLUSTRATION OF RENEWABLE INTEGRATION COMPLEXITY UNDER HIGH WIND/SOLAR SCENARIOS

As the penetration level of renewables increases, the complexity of integrating renewables may also increase, in some cases exponentially. A comparative graph like Fig. 4 visualizes two important metrics of integration complexity: renewable curtailment and powerflow. As shown in Fig. 4, which represents a typical high-wind generation hour (Table 1 shows the incremental wind capacity additions for the penetration milestones presented in this paper), the horizontal stack bars show the trend of renewable curtailments between milestones, as a proxy for the complexity of integrating renewables. For instance, wind curtailment in ND&MN increases significantly in 40% milestone, suggesting transmission could be the most critical bottleneck for integrating renewables even after introducing transmission solutions.

TABLE 1. **Incremental capacity addition of wind resources.**

Milestone	10%	20%	30%	40%
Capacity Wind (MW)	1,993	15,511	28,303	41,521

TABLE 2. **Incremental capacity addition of solar resources.**

Milestone	10%	20%	30%	40%
Utility-scale PV (MW)	1,050	8,500	15,575	23,125
Distributed Rooftop PV (MW)	1,276	4,711	8,549	12,257

The largest change in dispatch and subsequent power flows, on the other hand, show the possible system stress given transmission constraints. Thermal generation is also reduced as penetration increases across the footprint, and in the North regions, some LRZs have more than 90% renewable energy penetration levels.

Likewise, during periods of high solar generation, the system complexity also increases; however, this may have different implications when compared to the high wind conditions. Table 2 includes the incremental solar capacity by milestone. Given the model assumptions in RIIA, solar generation in high-renewable milestones typically reaches its peak in the MISO system between 11:00 a.m.(CST) and 6:00 p.m. (CST).

Fig. 5, which shows a typical high solar generation hour (12:00 p.m. (CST) on April 3, 2107), shows that the intra-regional flows, relative to high wind scenario illustrated in Fig. 4, are smaller in magnitude (The Appendix includes Fig. 5 in full resolution). However, the direction of flow follows a similar pattern. Another interesting observation that can be drawn from the stack bars in Fig. 5 is the lower level of renewable curtailment when solar generation is high. This observation is consistent with the understanding that the solar generation in general positively correlates with the load.

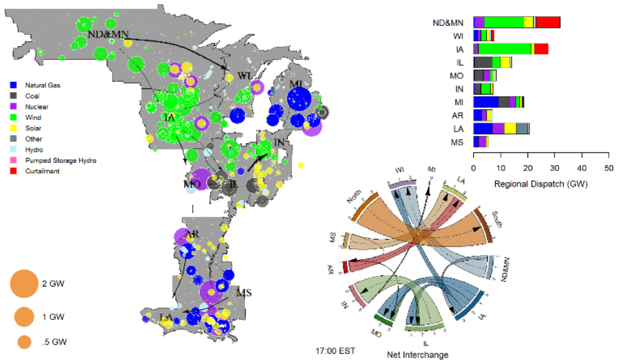

FIGURE 6. **40% milestone without solutions.**

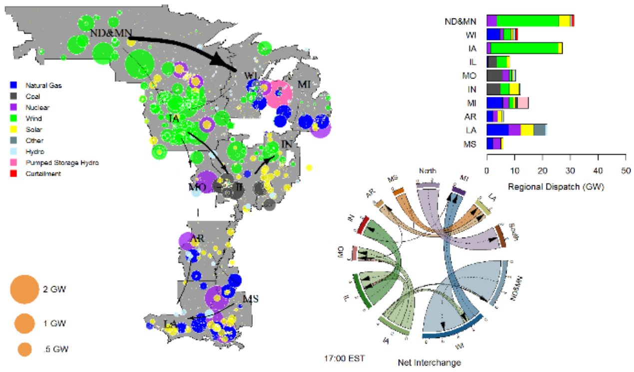

FIGURE 7. **40% milestone with solutions.**

C. TRANSMISSION SOLUTIONS AND ITS EFFECT ON THE ENHANCEMENT OF RESOURCE DELIVERABILITY

As renewable integration complexity increases, MISO finds that in addition to changing dispatch of existing thermal generation resources, transmission solutions are needed to increase the deliverability of renewables and are crucial for achieving higher penetration levels (e.g., 30% and above). In the RIIA study, MISO transmission optimization for developing transmission solutions. Candidates of transmission solutions are first screened based on several factors, including economics, land availability and right of way (ROW), voltage level, and thermal ratings. A filtering algorithm based on minimum spanning tree (MST) theory is then applied to all potential combination of connections, resulting in approximately 11,000 candidates across MISO's footprint. This set of candidates of transmission solutions includes line upgrades on existing paths, increasing the voltage level of an existing substation, and new line connections. A transmission optimization simulation is then performed for each RIIA milestones to obtain their respective final sets of transmission solutions. Kaleidoscope produced Fig. 6 and Fig. 7 as examples to illustrate the effect of transmission solutions on enhancing renewable deliverability. Figure 6 and Fig. 7 represent the same operating conditions, whereas the latter is with transmission solutions (the Appendix includes Fig. 6 and Fig. 7 in full resolution). By comparing the horizontal bar charts between these two figures, one can easily find that Fig. 7 provides evident visual illustration of the reduction in wind curtailment after including transmission solutions. The power flows on the geo-map further show the relative increase in power flow from renewable hubs to load centers, e.g., from ND&MN to WI as depicted by the thicker black arrow in the geographic visualization and the width of the ribbon in chord diagram. The transmission solutions identified in this work, using optimization techniques, resulted in a 9% curtailment reduction for MISO (e.g., renewable delivered increased from 34.7% to 38.5% for the 40% milestone). The 80 transmission solutions identified (existing lines upgrades and new lines) facilitated the integration of higher levels of renewables, and solved additional complexities related to operating reliability issues (e.g., thermal violations, frequency response, and stability).

Another time-lapsed animation included in Appendix (see Animation_40percent_with_solution) further illustrates how the existing thermal generation fleet responds to the larger intra-regional flows within the footprint after transmission solutions facilitate wind integration. For instance, generation from natural gas units changes more rapidly (over 7 to 9 hours) to meet most of the net-load following requirement. The magnitude of power flows from ND&MN to WI also significantly increases and reaches 3 to 4 GWs between hour 18 and 20 in this example.

D. SANITY CHECK OF SIMULATION RESULTS

Kaleidoscope and its comparative graphs are useful to visualize simulation results for ease of sanity checking. Quality control of data inputs and modeling outputs are essential in the RIIA study. The study offers two examples to illustrate how the RIIA team utilizes Kaleidoscope to verify that both the inputs and simulation settings are correct, as well as the reasonableness of simulation outputs.

1) EXAMPLE 1: DE-COMMITMENT OF NUCLEAR UNIT

In the RIIA study, nuclear units are modeled as must-run generation with a near-constant hourly dispatch, and nuclear unit retirements are neglected. Hence the RIIA team expects to see identical nuclear generation through 10% to 40% penetration milestones. However, in one of the early simulations, the RIIA team found that a nuclear unit in Mississippi was being de-committed at the 40% milestone, as illustrated in Fig. 8 (a big purple bubble disappears). In this example, the use of Kaleidoscope helps the analysts to spot such anomalies and make corrections in the simulation settings.

2) EXAMPLE 2: FAST RAMPING OF COAL UNIT

Similar to nuclear units, most thermal units, including coal and various types of gas-fired units, are modeled with a set of operational characteristics based on their technology type, including ramping capabilities and marginal cost, among others. In another set of simulation results spanning the 24- hour period (see Animation_coal_ramp in Appendix), the study team noticed that several coal units were committed and de-committed rapidly during sunset hours; however

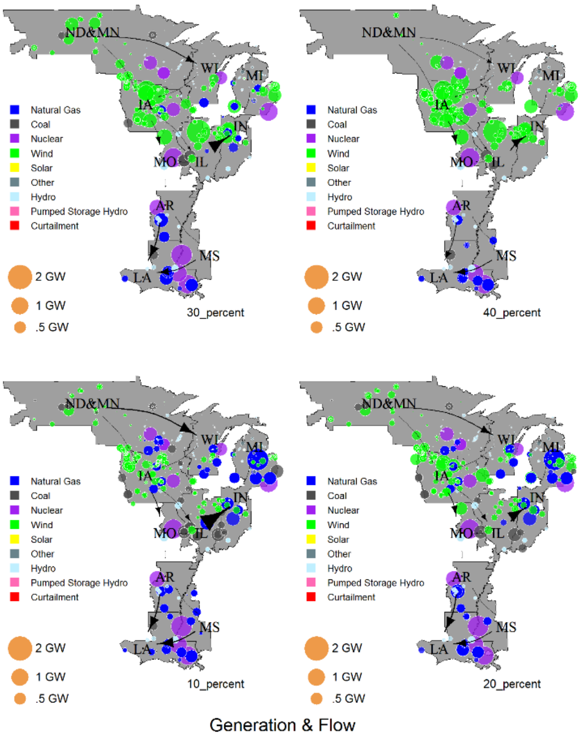

FIGURE 8. **Sanity check Example #1, de-commitment of nuclear unit.**

no violation of minimum generation level violations were reported. This finding led to further refinement of the operational input assumptions of conventional coal units.

V. CONCLUSION

This paper presented the extension and implementation of NREL's Kaleidoscope software to complement the current data analytics and visualization processes at MISO. The ability to visualize spatial-temporal data at different time scales, considering multiple aspects of renewable integration adds value to current analytic and visualization tools used at MISO. The framework developed in this work is currently being used in RIIA and further use of Kaleidoscope is expected in future work. For example, stakeholders within MISO's footprint could adopt the developments presented in this work for their own use. Furthermore, the Kaleidoscope package can also be extended to visualize other studies that similarly comprise temporal-spatial data. For instance, the interaction between gas pipeline system and the bulk electric system has drawn increasing attention in recent years, owing to continued retirement of coal plants, sustained low natural gas price, and concerns on fuel resilience. The study of gas-electric coordination requires understanding the interdependencies between two independent, yet related infrastructures. Including gas pipes and hubs into the current visualization framework, would allow analysts to illustrate the implications of gas pipes contingencies on the electric power grid, gas flow vs. electric flow, among other applications. The Kaleidoscope package can also be implemented to illustrate different resource expansion or generation interconnection studies. Finally, this work has the potential to be implanted in MISO's and other regional transmission operators' control rooms to enhance current monitoring visuals and provide operators with additional information.

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APPENDIX

In the Appendix which has been provided as supplementary material, we provide Fig. 4 through Fig. 7 in full resolution, and three time-lapsed animations for a 24-hour period.

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