

# Workshop Report

## Simulating Space Weather Extremes: A Workshop to Identify Research Needs to Improve Power Grid Resilience to Geomagnetic Activity

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## Executive Summary

In 2019, the Convergence Hub for the Exploration of Space Science (CHESS)<sup>1</sup> project was awarded as (to date) the only space science-focused project in the National Science Foundation's (NSF) Convergence Accelerator program.<sup>2</sup> The concept of the convergence accelerator is that national-scale societal challenges cannot be solved by a single discipline. Instead, these challenges require convergence: the merging of innovative ideas, approaches, and technologies from a wide and diverse range of sectors and expertise. CHESS brought this idea to the Sun-to-Society system, the goal being to understand the threats posed by space weather and to build more resilient societal infrastructure to address those threats, starting with the power grid. A workshop awarded through the NSF Space Weather Program (Award Number: AGS-2131047<sup>3</sup>) was held between April 12-14, 2022 in Washington DC as a natural evolution and next step for the CHESS project: "Simulating Space Weather Extremes: A Workshop to Identify Research Needs to Improve Power Grid Resilience to Geomagnetic Activity." The three-day workshop brought new understanding to the complex Sun-to-power grid system by converging the range of involved communities to identify the research and development and operational gaps and proposed solutions for those gaps. The novel workshop structured the convergence through a hypothetical space weather-to-power grid 'simulation game,' a low-risk, cost-effective

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<sup>1</sup> <https://www.chessscience.com/>

<sup>2</sup> <https://beta.nsf.gov/funding/initiatives/convergence-accelerator>

<sup>3</sup> [https://www.nsf.gov/awardsearch/showAward?AWD\\_ID=2131047&HistoricalAwards=false](https://www.nsf.gov/awardsearch/showAward?AWD_ID=2131047&HistoricalAwards=false)

environment to unite researchers, decision-makers, and operators to assess the preparedness for threats and hazards posed by space weather impacts on the electric power grid<sup>4</sup>.

### **Key Points:**

- ‘Simulation games’ are an important tool to facilitate convergent interactions, more cohesive and productive interactions between space weather researchers and a society affected by it; we created a template for all groups to use this tool
- For complex systems, like the Sun-to-power grid, it is vital to understand the information flow between and across the communities and disciplines involved; we created an information flow network for the Sun-to-power grid system and identified the communication between each node via R&D gaps and ‘wishlists’ (what each community needs from the other)
- We provide a full synthesis of the R&D gaps we discovered, associated recommendations, and a database of lessons learned for future groups to conduct convergent interactions, more cohesive researcher-user collaboration, and simulation games

## **Introduction**

At 2 a.m. on February 15, the Electric Reliability Council of Texas (ERCOT) declared an Energy Alert Level 3 and utilities began rotating outages due to high consumer demand. The heightened alert was the result of ERCOT officials nervously watching the frequency of the electric power grid

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<sup>4</sup> <https://www.fema.gov/emergency-managers/national-preparedness/exercises>

drop outside of the narrow 60 hertz band, a number affected by innumerable moving pieces and dynamics from the weather to the operation of the power grid to the user demand on the system.

The events of February 2021 reawakened the world to the precarity of the power grid, a massively complex and integrated system whose resilience in the face of the variability of the natural and human world is anything but guaranteed. The way we see and attempt to control the grid is like trying to know everything about a room we aren't standing in when all we have is a temperature reading from a thermometer within it.

The grid is at the whim of the myriad forces of the natural world and the vicissitudes of human behavior, a truly complex system<sup>5</sup>. Now, as our Sun's cycle ramps back up in activity, we are again being reawakened to a threat to the power grid that has the potential to push the system beyond its tipping point. Space weather is a global and imminent threat, falling in the same likelihood of occurrence in the next five years as “pandemic influenza” on the United Kingdom Risk Registry [UK Cabinet Office, 2017], but in some ways we are less prepared for a space weather disaster than a pandemic. Progress is precluded by an artificial separation of the relevant disciplines.

***To reimagine grid resilience, data from diverse fields must be open and broadly usable and the traditionally disparate communities must be connected.***

On April 12-14, 2022 a convergent<sup>6</sup> group crossing the Sun-to-Power Grid system ran a space weather ‘simulation game,’ low-risk, cost-effective environment to unite researchers, decision-makers, and operators to assess the preparedness for threats and hazards posed by space weather on the electric power grid through a hypothetical event.

***We have attempted to make this report useful and usable by providing three items: Articulated research and development (R&D) gaps, recommendations based on the R&D gaps, and ‘Wishlists’ for each link in the information flow in the Sun-To-Power Grid system. Recommendations are provided upfront and R&D gaps and wishlists are provided in the Achievements Section.***

The group that gathered included representatives from the National Science Foundation, NASA, Department of Energy, Federal Emergency Management Agency (FEMA), Federal Energy Regulatory Commission (FERC), North American Electric Reliability Corporation (NERC), United States Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA), several national space weather programs, and numerous academic and private institutions. A full list of individuals and institutions are provided in Appendix A, noting that a much larger community was engaged in preparing for this event that was not able to attend in person.

The central goal of the workshop was to identify the R&D gaps that arise from a holistic view of the Sun-to-Power Grid system, responding to the question: ‘What will affect me that I am not

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<sup>5</sup> [https://www.youtube.com/watch?v=R4f1NM\\_a6VU](https://www.youtube.com/watch?v=R4f1NM_a6VU)

<sup>6</sup> <https://www.nsf.gov/od/oia/convergence/index.jsp>

aware of now?’ for all members of the Sun-to-Power Grid chain. Auxiliary goals were twofold: **1)** create a community-wide exercise to run models and trace communication lines. This required identifying resource requirements, capability gaps, strengths, areas for improvement, and potential best practices and exploring the communication pathways, data analyses, and responses that an extreme space weather storm triggers and assess the strengths and weaknesses of the research capabilities and operational system; and **2)** cultivate a more cohesive Sun-to-Power Grid community and promote more robust channels of communication based on the pathways discovered in the course of the simulation game, including the future technological information systems needed.

Questions that animated us throughout the week and that will continue into the future are:

- What are the research & development and operational gaps that emerge from a **holistic** view of the Sun-to-Power Grid system and what solutions can we imagine to address them?
- What is the composition of the teams that can create these solutions?
- How do we connect these gaps to existing programs and form bridges across them?

This workshop emerged from a paradigm-shifting approach to Sun-to-Power Grid research, development, and operations that occurred through the Convergence Hub for the Exploration of Space Science (CHESS) project. That project adopted a convergence approach, or a radical merging of innovative ideas, approaches, and technologies from a diverse range of sectors and expertise. CHESS created an information flow for the Sun-to-Power Grid System (Figure 1).

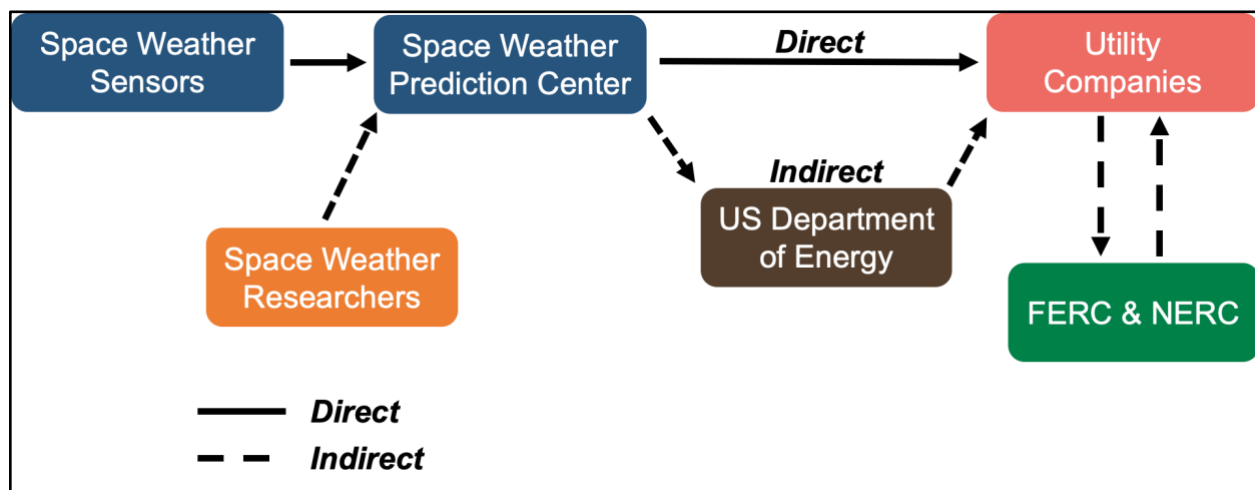


Figure 1: High-level Sun-to-Power Grid Information Flow Diagram defined by the CHESS Project.

The workshop, using the Sim Game Boundary Navigating Object<sup>78</sup>, improved and enriched that diagram, which organizes and makes actionable the workshop outcomes. The following diagram,

<sup>7</sup> [https://en.wikipedia.org/wiki/Boundary\\_object](https://en.wikipedia.org/wiki/Boundary_object)

<sup>8</sup> Boundary objects are information that different communities use to coordinate communication, thereby facilitating cross-disciplinary collaboration. Boundary objects are entities that can link communities together as they allow different groups to collaborate on a common task [Wenger, 1998]. These ‘objects’ are typically things with a standardized structure such as forms, maps, and grades [Lee, 2007]

created by Alicia Juarrero, will be used to identify intervention points for the Sun-to-Power Grid community, ***for the purpose of improving the resilience of the power grid.***

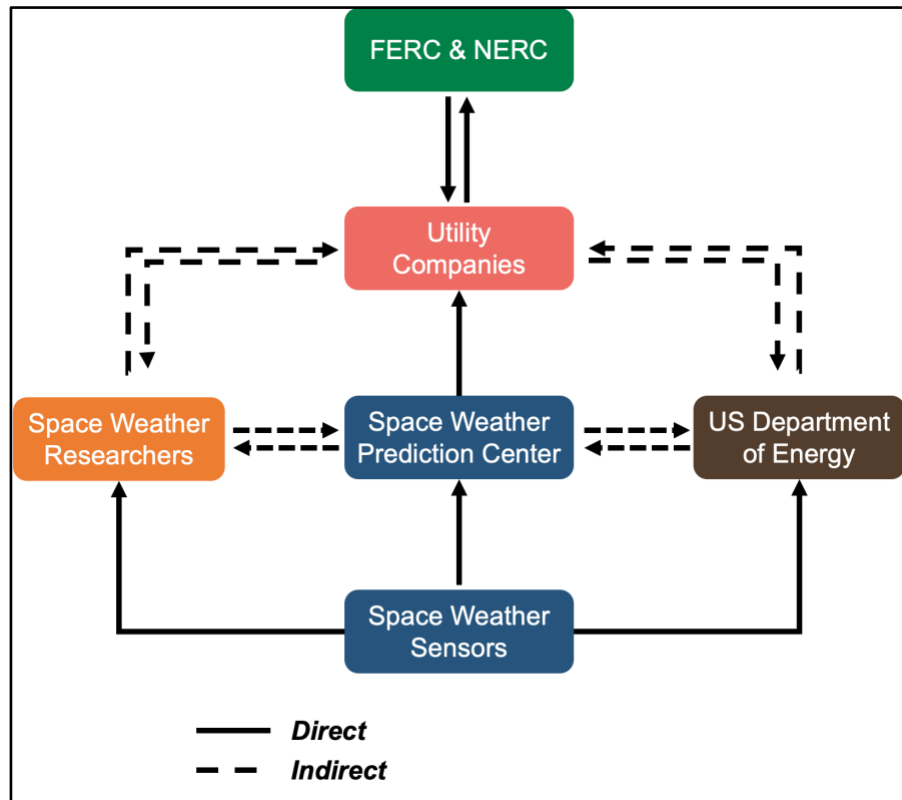


Figure 2: Sun-to-Power Grid Information Flow Diagram (Figure 1) extended by Alicia Juarrero and then iterated upon during the workshop.

In the remainder of this report we first describe the overall recommendations from the event. We then detail the design of the simulation game and workshop and a summary of the actionable outcomes. The appendices provide comprehensive reports for the: 1) actionable recommendations (Appendix A); 2) R&D gaps (Appendix B); and 3) wishlists for each link in the information flow diagram that will be translation points/handshake items between each entity in the convergent community, and shows ways to support sustained conversations among them (Appendix C). Finally, we provide in-depth details about the event participants (Appendix D) and agenda (Appendix E).

## Overall Recommendations

Recommendations are the synthesized guidance for the Sun-to-Power Grid community based on the lessons learned, gaps analysis, and observations across the entire lifecycle of the workshop (proposal, design, convening, conclusion).

There are several key recommendations from the workshop:

1. Support convergent research activities, including the nontraditional, cultural, elements of facilitating cross- and trans-disciplinary interactions.
2. Clarify roles and responsibilities of each entity in the Sun-to-Power Grid information flow to create more granular understanding of where and how interactions should occur. To support those interactions, create 'wishlists' that can become clear interaction points between communities (e.g., what power grid engineers need from space weather researchers).
3. Have wider space weather community participation in future power grid events, such as the North American Electric Reliability Corporation (NERC) GridEx<sup>9</sup>, the largest grid security exercise in North America, and the Electric Power Research (EPRI) Sunburst<sup>10</sup> meetings, as well as power grid community conferences and meetings. Conversely, invite power grid individuals and groups to space weather events. These cross-community interactions support extensive user interactions, which space weather researchers and institutions frequently perform, but information from which is rarely shared across teams or synthesized for broader space weather community use.
4. Run more simulation games as activities (boundary navigating objects<sup>11</sup>) for these convergent interactions.
5. Acknowledge that data and knowledge interoperability is not just within the space weather community, but that wider metadata standards for data provision and description should be utilized. There has been no holistic effort toward glossary harmonization or developing shared vocabulary for the Sun-to-Power Grid.

## Design of the Event

Our intention was to create an inclusive, informed, and cohesive atmosphere so that the workshop would run smoothly and enjoyably. To support that we first created an opportunity for all workshop attendees to virtually connect, get to know each other, and begin to understand one the languages of the various fields involved. This was achieved through a pre-workshop virtual 'micro-lab.' The micro-lab was important to a more efficient use of in-person time.

Additionally, we created a set of resources to provide means for participants to begin interacting prior to meeting in-person, including:

- [Slack space for our workshop](#). This place for exchange will remain active beyond the event. It will be a place for us to have fluid conversations and to engage with the community that is not present at the event

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<sup>9</sup> <https://www.nerc.com/pa/CI/ESISAC/Pages/GridEx.aspx>

<sup>10</sup> <http://sunburstproject.net/index.html>

<sup>11</sup> [https://en.wikipedia.org/wiki/Boundary\\_object](https://en.wikipedia.org/wiki/Boundary_object)

- [Micro-Lab Miro Board](#)
- [CHESS + Workshop Github](#) (for scripts and small data files)
- [Zotero Library for document/publication sharing](#)

Finally, we embraced an ethos of open science and broadening participation and healthy communication by convening a special panel event<sup>12</sup> to occur in connection with the workshop and be freely open and offered virtually. The panel was titled "Research and Development (R&D) Opportunities" and helped identify needed projects and applications related to R&D gaps in the Sun-to-Power-Grid system and share those with the community through dialogue. The panel was vital for providing ideas for the broader community to bring back to their research and operational settings and to spur transdisciplinary collaboration and convergence.

To design the simulation game itself we began by embracing the idea of 'worldbuilding.' Worldbuilding is the process of creating and adding details to an imaginary setting, either as a fictional work, hobby, or way to generate conversation about a topic. This is what brings the simulation game to life. To bring the new world of the simulation to life, we conducted extensive interviews to learn the process of creating and facilitating a tabletop exercise/simulation game. Those interviews included:

- FEMA tabletop exercises<sup>13</sup>
- GridEx<sup>14</sup> and NERC E-ISAC
- Cynefin Framework<sup>15</sup> and Dave Snowden
- Warm Data Labs<sup>16</sup> and Nora Bateson
- Institute for the Future<sup>17</sup> and Jane McGonigal
- Triple Threat Power Grid Exercise: High Impact Threats Workshop and Tabletop Exercises Examining Extreme Space Weather, EMP and Cyber Attacks [*Baker et al.*, 2015]
- Social science and Julie Demuth [*Morss et al.*, 2021].

We used the simulation game as a "[boundary object](#)," a tool that facilitates cross-disciplinary communication among disparate communities, allowing them to collaborate on a common task and develop a shared language [*Star and Griesemer*, 1989; *Lee*, 2007; *Wenger*, 1998]. The game served to structure interactions and to enhance connections and information exchange, or "idea flow" [*Pentland*, 2014], among participants beyond what would have been possible through traditional presentation formats. These interactions involved interleaved exploration (brainstorming) and engagement (coordinating) activities [*McGranaghan et al.*, 2022a].

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<sup>12</sup> [https://www.eventbrite.com/e/chess-simulating-space-weather-extremes-workshop-rd-opportunities-panel-tickets-315683276177?keep\\_tld=1](https://www.eventbrite.com/e/chess-simulating-space-weather-extremes-workshop-rd-opportunities-panel-tickets-315683276177?keep_tld=1)

<sup>13</sup> <https://training.fema.gov/programs/emivttx.aspx>

<sup>14</sup> <https://www.nerc.com/pa/CI/ESISAC/Pages/GridEx.aspx>

<sup>15</sup> [https://cynefin.io/wiki/Main\\_Page](https://cynefin.io/wiki/Main_Page)

<sup>16</sup> <https://batesoninstitute.org/warm-data-labs/>

<sup>17</sup> <https://www.iftf.org/home/>



Workshop participants were sequentially presented with a narrative for each simulation phase, along with data visualizations, model outputs, and other elements to bring the scenario to life (e.g., news headlines, social media, etc.). After each phase was presented, they convened separately in four discussion groups to work through a list of prompts carefully designed to facilitate a common group effort and shared language. These prompts included, for example, questions about uncertainties in space weather models and how quickly model updates are produced and shared, and about how decisions by grid operators to take action in light of risks to power supplies are coordinated [[McGranaghan et al., 2022a](#)].

In addition to the predetermined prompts, group leaders also facilitated open-ended discussion to further promote idea flow and connections among participants. And following each discussion session, group leaders wrote up summaries of key ideas, questions, and recommendations to share and integrate with those of other groups [[McGranaghan et al., 2022a](#)].

To realize the full design (of the simulation game as well as the full event) the Steering Committee worked together biweekly for more than eight months to design, refine, and finalize the workshop structure and simulation game. Simultaneously, we created a Design Team, a small group (no more than 5-6 individuals) of active individuals responsible for facilitation and coordination during the workshop and simulation game, that interacted more frequently and took leadership roles. Our group consisted of the director of the workshop and four individuals who each served as simulation game discussion group leads and provided readouts from those discussion groups. A number of sub-groups emerged to generate the data for the simulation game. Those sub-groups were loosely organized into four sectors: space weather, geoelectric field, power grid, and socioeconomic. Sub-groups interacted frequently and there were less frequent, but regular, cross-sub-group interactions to share data. Those crossover meetings revealed the parameters and variables that are key exchange points between communities and identified procedures for sharing those data (e.g., format) and the metadata that were required to effectively share.

## Communication

A topic emerged during the final day discussions of how to sustain the momentum and conversations from the workshop. The Steering Committee anticipated this and created a structure for uncommon communication, dissemination, and cross-media exchange that they believed would be a more resilient means to amplify the workshop momentum. The approach centered on the idea of a *knowledge commons* [[McGranaghan et al., 2021](#)]. Elements of the communication efforts included:

- Public website for the workshop<sup>18</sup> that created engagement during planning phase of the workshop and helped the Steering Committee understand interest and active work in the community
- PubPub offers an open access collaborative publishing platform, ideal for living articles and community curation of published material. The Space Collection was created to be an attempt to be an open publishing platform for the space physics, Heliophysics, and space weather communities to write pieces that may not fit in other publishing venues. This could be anything from a long-form research piece or a blog-like post/short essay. We wrote an essay for that collection [McGranaghan *et al.*, 2022b]. This collection is part of the goal of the workshop to create a **knowledge commons** [McGranaghan *et al.*, 2021]. The knowledge commons also include data created or curated as part of the simulation game, the data analysis resources (e.g., software), and community collaboration resources (e.g., Slack) (see Knowledge Commons section under 'Prior Achievements' below). The R&D gaps, wishlists, and lessons learned provided as artifacts of the workshop are extensions of the knowledge commons.

Post-workshop, focus will be placed on dissemination and specifically multifaceted communication that can cross disciplinary and community boundaries. This report is a piece of that communication and broader engagement, as was the public virtual panel session that we held on the final day of the event. Other forms include:

- Create a publicly available template for this simulation game for broad community use and running new instances of simulation games
- Conference presentations (e.g., invited talk at Space Weather Workshop 2022<sup>19</sup>)
- PubPub essays contributed by participants (open publishing)
- Curated resources made broadly available
- Virtual 'micro-labs' to continue and expand conversations
- Create a new space for special publications devoted to research-to-operations (R2O), which is distinct from research manuscripts and operations manuscripts.

## A Playbook for Driving Convergence

Convergence is about working on societal problems that have been obstinate to progress because they do not fit into any existing academic discipline and that require a new paradigm and novel approach. Convergence alludes to the existence of profound new opportunities to transform research across all fields of science and engineering. Fields primed to benefit from the convergence approach are those grappling with the co-evolution of: 1) drastic data growth; 2) increased sophistication of data-intensive computing capabilities; 3) data science technologies; and 4) proliferation of the involved/affected communities. The trend is a shifting

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<sup>18</sup> <https://www.chessscience.com/sim-game-workshop>

<sup>19</sup> <https://cpaess.ucar.edu/space-weather-workshop-2022>

digital, data, and cultural landscape and the impact is felt across all fields of science and engineering. Community-wide, we face an exciting opportunity and important imperative to transform research by connecting a wider diversity of expertise. However, convergence is a challenge for numerous reasons, not the least of which is that our existing approaches to collaboration and understanding one another may be inadequate to the scale our grand societal problems require.

This workshop led to the refinement of a *playbook* for achieving convergence and its use for all individuals to create better interactions is a broad impact of this event.

The high-level items of the playbook are:

- Adopt a human-centered design approach
- Think in networks: understand the relationships between disciplines, datasets, models, and projects
- Use data science to make these connections: the Open Knowledge Network
- Embrace the Science of Team Science
  - Dynamic nature of collaborations; center around questions not domains, problems not traditions

Part of this is the creation of a sim game template/playbook/curriculum/package that everyone can use, tailor, improve to their needs.

## How we gather and the under-valued skill of organizing and facilitating

This workshop was uncommon in its focus on design of interactions and facilitation. It revealed an under-valued and perhaps under-appreciated skill of organizing in the sciences, the art of gathering and facilitation. We believe new knowledge of these skills and their centrality in 21st century science/the science of complex problems/cross-disciplinary science is an important outcome of the workshop in addition to the R&D outcomes. We have captured many lessons learned about gathering convergent groups in our Lessons Learned Database<sup>20</sup> and will be producing longer-form pieces to share broadly.

[McGranaghan et al., \[2022a\]](#) describe in more detail the skills of organizing and facilitation and the importance to the scientific community.

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<sup>20</sup> <https://docs.google.com/spreadsheets/d/1Ed60-YoQXyqM63mAWp2QXcr58pHpqh2nHDZB838AOIk/edit?usp=sharing>

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## Appendix A: Comprehensive Recommendations

Recommendations are the synthesized guidance for the Sun-to-Power Grid community based on the lessons learned, gaps analysis, and observations across the entire lifecycle of the workshop (proposal, design, convening, conclusion).

- Produce and iterate a 'playbook' for making your research/meetings/conversations more convergent
- Outline for space weather community the hierarchy of power grid roles and responsibility levels (e.g., Reliability Coordinations, Regional Transmission Operators, Utility Managers, Utility Operators) and specify what each level cares about
  - Communicating these 'levels' of users to space weather domain would be valuable
  - These levels will not have the same considerations and information needs from the space weather community
  - In general, more training and education for space weather side about power grid needs (there are some FEMA modules being developed that are a good starting point)
  - Develop clear materials for the space weather community to understand power grid domain reporting structure. Start with [Federal Operating Concept for Impending Space Weather Events](#)
- Encourage wider space weather community participation in future events, such as the North American Electric Reliability Corporation (NERC) GridEx<sup>21</sup>, the largest grid security exercise in North America, and the Electric Power Research (EPRI) Sunburst<sup>22</sup> meetings, as well as power grid community conferences and meetings.
  - Learn from the more mature collaborations, like those with the aviation industry (e.g., how were those relationships developed?).

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<sup>21</sup> <https://www.nerc.com/pa/CI/ESISAC/Pages/GridEx.aspx>

<sup>22</sup> <http://sunburstproject.net/index.html>

- We need to establish a list of the generative questions that space weather and power grid communities can use to interact around
  - Space weather researchers need to be given opportunities to articulate their needs/questions of the power grid.
- In future Research-to-Operations and Operations-to-Research (R2O2R) activities, provide outcomes in the form of a *wishlist*, to provide clear points of interaction between communities.
- Run more simulation games as activities (boundary navigating objects<sup>23</sup>) for these convergent interactions
  - Repetition is key for insight generation and knowledge crystallization
- Have an open space weather contribution to creating software around NERC GIC database<sup>24</sup> that enriches those data and makes them more usable
- Make user exploration a community-wide collaborative effort (better sharing and synthesis across groups, programs, and projects conducting user surveys and interviews)
- Produce a study of the full reliance of power grid functions on telecommunications (beyond just sustaining baseline communications to cover e.g., ability to make bank transactions/payments)
- Incentivize, support, and adopt a complex systems approach to the power grid
- Engage Critical Interdependencies: the interconnectedness of critical infrastructure and society at large require that in future activities the Sun-to-Power Grid community needs to increase the participation of other interdependent organizations, including natural gas utilities, water utilities, and telecom companies/providers/agencies
- Whole-of-power grid coordination: Explore equivalent programs for space weather to the 'Cyber Mutual Assistance (CMA)' for responding to cyber threats to the power grid
- A challenge to convergence (especially for the Sun-to-Power Grid system) is shared vocabulary. It is insufficient and unproductive to attempt to assign one definition to terms, we need to instead target *glossary harmonization*. These conversations should occur upfront in all convergent meetings, teams, workshops.
- Acknowledge that data and knowledge interoperability is not just within the space weather community, but that wider metadata standards for data provision and description should be utilized. There has been no holistic effort toward glossary harmonization or developing shared vocabulary for the Sun-to-Power Grid.
- Business and population impact needs to factor into the risk calculation and be presented to space weather researchers and power grid engineers. Platforms that can overlay these models on space weather hazards and power grid vulnerabilities are required.
- Identify the science questions that require large-scale integration and computational efforts. This is a way to engage with the Department of Energy through the Advanced Scientific Computing Research
- Create a new space for special publications devoted to research-to-operations (R2O), which is distinct from research manuscripts and operations manuscripts.

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<sup>23</sup> [https://en.wikipedia.org/wiki/Boundary\\_object](https://en.wikipedia.org/wiki/Boundary_object)

<sup>24</sup> <https://www.nerc.com/pa/RAPA/GMD/Pages/GMD-Training.aspx>

- Collaborate with mediating groups, like EPRI, become better connected to the research community
- Learn from other geographical regions/countries (e.g., Canada, New Zealand) and from other disciplines (e.g., spacecraft anomaly, Biomedical) about how cross-disciplinary relationships have been developed
- Community coordination requires uncommon approaches, including:
  - Improve our ability to gather and share knowledge across groups larger than 10s of people
  - deeper consideration of how we gather and communicate. It is not enough just to have all these people in the same room and to have a series of presentations. We need multifaceted and multi-level and multiscale forms of communication and connecting
  - Make user exploration a community-wide collaborative effort (better sharing and synthesis)
  - Borrow from the fields of social science, psychology, and team science to improve communication and collaboration. For instance, use of 'boundary navigation objects' like a simulation game

## Appendix B: Research and Development Gaps Identified

A gap is a shortcoming or opportunity based on a difference between state-of-the-practice and an ideal state. In this case, the ideal state is a resilient power grid. Our gap analysis emerged five vital categories, shown in Figure 3. Note that models are an integral part of the system of resources we must consider and address, however they are not explicitly represented in Figure 3 below because much of the discussion concerning them centered on their construction, validation, and trustworthiness and therefore on the observations and communications that undergird those elements of models.



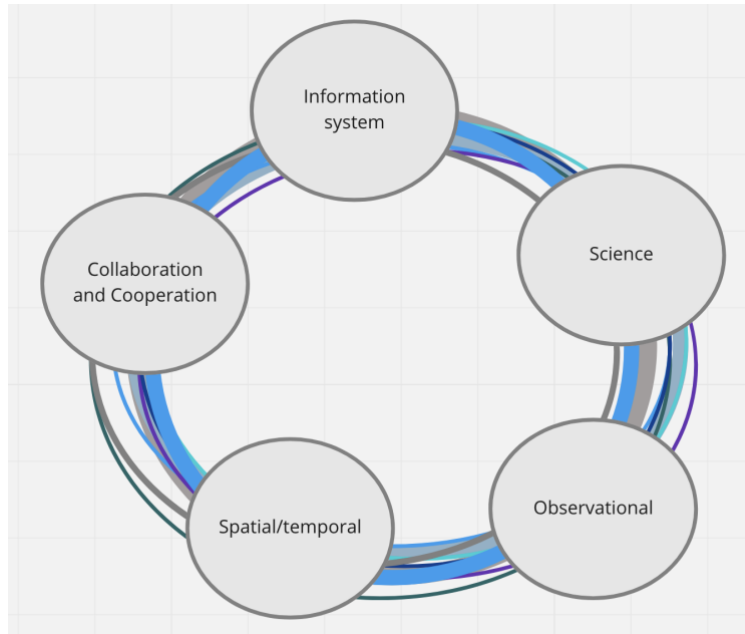


Figure 3: The five categories of gaps: Science, observational, spatial/temporal, information system, and collaboration and cooperation.

Below are the gaps that we identified in each category. The nature of these gaps is that they may not neatly fall into these categories and contain connections to numerous categories. They may be more appropriately represented as a *network*<sup>25</sup>. We provide such a network representation and a living artifact to explore the gaps in the public Miro board for this workshop<sup>26</sup>. The password to access is 'chess\_ws'. We note that this was a three-day event, so certainly not sufficient to describe in detail all of the gaps. There are therefore omissions that readers will know and our descriptions of the gaps are in many places slight or more of the note variety than a detailed articulation. We present them here as a faithful representation of the workshop discussions and in the hope that what is not fully described or absent from the bulleted lists will be generative of future research.

## Spatial/Temporal scale gaps

- The granularity of space weather information available to power grid utilities is inadequate
  - Need multi-scale spatio-temporal information that also cuts across domains and can fill in the scales in space and time where large uncertainty remains in space weather
- Power grid utilities do not have a good understanding of how a neighboring regional coordinator's region action will affect our own
  - Suggestion that a mutual program (like Cyber Mutual Assistance<sup>27</sup>) would be valuable
- The work and needs of power grid and space weather communities involve different scales

<sup>25</sup> <http://networksciencebook.com/>

<sup>26</sup> [https://miro.com/app/board/uXjVOKMgMfw=?share\\_link\\_id=28073673510](https://miro.com/app/board/uXjVOKMgMfw=?share_link_id=28073673510) with password: chess\_ws

<sup>27</sup> <https://www.electricitysubsector.org/CMA/>



- Power grid does not know how to confront the question of the accuracy needed vs the accuracy currently attainable
  - There is uncertainty in knowing the resolution of geoelectric field resolution needed and in creating systems that can serve different resolutions to different regions and power grid operators.

## Science gaps

- We still do not know what an extreme event looks like: produce more physically meaningful extreme event scenarios.
- We need to treat the Sun-to-Power Grid as a complex system.<sup>28</sup> A few specific points about complex systems approaches:
  - For instance, we need to better understand the information content of geomagnetic activity indices and information theoretic approaches are warranted (e.g., *Johnson and Wing*, [2019]).
  - With our space weather models as with our power grid networks we believe in 'fail safes' and need to believe in 'safe fails.' Complexity science offers a means to do science and engineering for resilient systems [*Scheffer*, 2009]. We do not understand the warning signs of approaching instability. To understand resilience, a network science approach is needed, yet there is little application of network science that encompasses space weather and the power grid
- The physical mechanism of GMD/GIC needs to be further identified and modeled using real and synthetic data
- Information system gaps exist and there is a paucity of investigation of the connections between space weather events and GIC via information theory, such as, mutual information
- We need improved models (supported by more observations, validated, and trustworthy) of the sun-Earth system that better capture the physics of the system

## Observation gaps

- Solar wind upstream conditions: Although NOAA SWPC provides long-term warnings of impending geomagnetic storms, it makes no geoelectric field prediction until observations are made at L1. We don't have ability to produce geoelectric field maps until a transient arrives a L1
  - Long-term solution: Satellites upstream of L1
  - Short-term solution: Machine learning models predicting solar wind conditions
- Magnetometer coverage and specifically making sure those deployments feed into SuperMAG initiative<sup>29</sup>

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<sup>28</sup> <https://www.santafe.edu/what-is-complex-systems-science>

<sup>29</sup> <https://supermag.jhuapl.edu/>

- These observational gaps are more comprehensively explored in the *Space Weather Science and Observation Gap Analysis for NASA report* from April 2021<sup>30</sup>.

Note that Figure 2 includes “observations” but does not explicitly mention “models.” We point out here models are utilized in at least 3 of the boxes in the figure: SWPC, Utility Companies, and Researchers.

## Information system gaps

An information system is a technology that provides the structure that allows data to be collected, stored, processed, and integrated. These systems are the structure that elevates data to information and ultimately knowledge. The field of data science is largely concerned with building more capable information systems and the analyses that can be layered on top of them [McGranaghan *et al.*, 2017]. We discovered that the information systems that are capable of serving the convergent Sun-to-Power Grid community are inadequate and are an element of the need for using convergence to create a more resilient grid:

- Disconnects exist across the Sun-to-Power Grid information flow (see Figure 2)
  - The visual/interactive presentation of multi-domain data to power grid engineers must be improved and made searchable
- We need the capability to overlay various hazard/risk/vulnerability maps on one another. Need nation-wide hazard maps that translate research outputs into hazards
- Compounding effects are key, but we often isolate space weather
  - Space weather never happens in isolation. Wind and terrestrial weather are inextricable from the considerations of a space weather event. There is a lack of integration of space weather with terrestrial weather.
  - There is disagreement on the degree of reliance on interconnections between societal infrastructure (e.g., Disagreement on the extent of the effect of GPS availability/functioning on the power grid)
- Information systems can be improved through semantic technologies and knowledge engineering
- Acknowledgement that interoperability is not just within the space weather community, but that wider metadata standards for data provision and description should be utilized (e.g., the compounding disaster group with National Science Foundation’s (NSF) Innovation Sprint<sup>31</sup> could trivially include space weather data if this is done properly)

## Collaboration and cooperation gaps

Within the collaboration and cooperation category are a number of emergent themes: coordinating across the Sun-to-Power Grid community, generating collaboration across regional areas and power grid utilities, addressing learning/educational shortcomings, and building trust.

<sup>30</sup> [https://science.nasa.gov/science-pink/s3fs-public/atoms/files/GapAnalysisReport\\_full\\_final.pdf](https://science.nasa.gov/science-pink/s3fs-public/atoms/files/GapAnalysisReport_full_final.pdf)

<sup>31</sup> <https://beta.nsf.gov/funding/opportunities/encouraging-research-open-knowledge-networks>

- There is a lack of cooperation between neighboring power grids, limiting regional knowledge
  - We may need whole-of-power grid coordination: there is no equivalent program for space weather to the 'Cyber Mutual Assistance (CMA)<sup>32</sup>' for responding to cyber threats to the power grid
- Coordinating across communities remains a challenge
  - All space weather programs are conducting user surveys/interviews, yet there is a lack of convergence and cooperation among these efforts and information
  - In order to prevent reinventing one another's work and efforts we need to improve our ability to gather and share knowledge across groups larger than 10s of people
  - Convergence requires deeper consideration of how we gather and communicate. It is not enough just to have all these people in the same room and to have a series of presentations. We need multifaceted and multi-level and multiscale forms of communication and connecting
- The flow of information is mostly one direction: from space weather to the power grid. We need to open up bidirectional communication. There is a lack of understanding the feedback needed from the power grid back to space weather, as well as the information that must flow across all entities in the Sun-to-Power Grid system (see Figure 2).
- Building trust is vital and is multifaceted:
  - Trust in space weather models: Probabilistic models are vital to producing confidence and subsequently trust in space weather models, yet most are deterministic. This is how risk is communicated.
  - There is a lack of granularity in the definition of 'Research to Operations' (R2O). Clarity can direct targeted space weather observational needs. This is connected to the information system and observational categories, too.
- Targeted learning/education for both the space weather and power grid communities are required.
  - On the space weather side, researchers need to understand that there are real costs associated with actions being initiated on the grid. Space weather information is not typically connected to power grid mitigative actions. Additionally, space weather researchers need to develop and understanding of the hierarchy of power grid roles and responsibility levels (e.g., Reliability Coordinations, Regional Transmission Operators, Utility Managers, Utility Operators) and specify what each level cares about.
  - On the power grid side, clarity must be provided about the resolution of space weather model products that are impactful. Power grid individuals must help identify the connections between space weather model output and power grid mitigative actions and impacts on profitability (metric of value for power grid utilities)
  - Business and population impact needs to factor into the risk calculation and be presented to space weather researchers and power grid engineers

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<sup>32</sup> <https://www.electricitysubsector.org/CMA/>

- There is little real- or post-event experience for space weather events on the power grid like there are for earthquakes or hurricanes. The feedback from these post-event periods is critical. Simulation games can help address this.
- We need the capability to overlay various hazard/risk/vulnerability maps on one another
  - Need nation-wide hazard maps that translate research outputs into hazards
- There is input from space weather to power grid, but relative lack of feedback from power grid back to space weather
  - What are the channels of this feedback? What new ones could we open? (outcome of this workshop is opening these new channels)
- Compounding effects are key, but we often isolate space weather
  - Wind and terrestrial weather are inextricable from the considerations of a space weather event
  - Space weather never happens in isolation
- Ground-based magnetic awareness
  - Magnetometer coverage and specifically making sure those deployments feed into SuperMAG initiative
  - Determine the information content of geomagnetic indices
    - Information theoretic approaches
- Lack of granularity in definition of R2O
  - targeted space weather observational needs
- Complex systems
  - Lack of understanding of feedback in the system (i.e., the role of context)
  - We believe in 'fail safes' and need to believe in 'safe fails'
  - We do not understand the warning signs of approaching instability (signs you are running out of adaptive capacity)
  - To understand resilience, a network science approach is needed, yet there is little application of network science that encompasses space weather and the power grid
- Vocabulary/knowledge engineering
  - Glossary harmonization
  - Clear and agreed upon definition of space weather (==how natural space environment affects societal infrastructure)
- Availability of power grid data
  - No clear path to how more GIC data will be made available to space weather community
  - In absence of GIC data, what other technologies/observations are available? Synchrophasors (PMUs) and electromagnetic sensors possible
- Power grid coordinated efforts
  - Whole-of-power grid coordination: there is no equivalent program for space weather to the 'Cyber Mutual Assistance (CMA)<sup>33</sup>' for responding to cyber threats to the power grid

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<sup>33</sup> <https://www.electricitysubsector.org/CMA/>

- Everyone is doing user survey (all agencies and activities) - there is a lack of convergence and cooperation among these efforts and information
    - Recommendation: Make user exploration a community-wide collaborative effort (better sharing and synthesis)
- Power Grid-to-Space Weather wishlist/gaps list
  - Forecast translated to V/km and with confidence intervals
    - Can plug this into their models
  - Regional forecast (fits the size of PJM)
  - Time series characteristics (conservative is fine)
    - E.g., time constants of heating of transformers
  - Model validation (the point at which community needs to come together and handshakes need to happen)
  - We need to work to continually refresh the 1/100-year storm
    - Start with TPL007 to understand how it is represented (e.g., V/km)
    - Localized hot spots
    - Time series signatures (scaling of historic storms is not sufficient)
- Team Science/Collaboration
  - In order to prevent reinventing one another's work and efforts we need to improve our ability to gather and share knowledge across groups larger than 10s of people
    - Convergence requires deeper consideration of how we gather and communicate. It is not enough just to have all these people in the same room and to have a series of presentations. We need multifaceted and multi-level and multiscale forms of communication and connecting
  - Lack of shared vocabulary. There has been no holistic effort toward *glossary harmonization*
- Disagreement on the extent of the effect of GPS availability/functioning on the power grid
  - Recommendation: produce a study of the full reliance of power grid functions (beyond just sustaining baseline communications to cover e.g., ability to make bank transactions/payments) on telecommunications
- Disconnects exist across the sun-to-power grid information flow
  - The visual/interactive presentation of multi-domain data to power grid engineers must be improved and made searchable

## Emergent project ideas to sustain interactions and begin to respond to R&D gaps

The final day of the workshop was for System-Building. We first broadened participation by offering a fully and virtually open panel session<sup>34</sup> to synthesize the workshop and share our findings. We then identified projects/areas of need that respond to the R&D gaps. These projects

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<sup>34</sup> [https://www.eventbrite.com/e/chess-simulating-space-weather-extremes-workshop-rd-opportunities-panel-tickets-315683276177?keep\\_tld=1](https://www.eventbrite.com/e/chess-simulating-space-weather-extremes-workshop-rd-opportunities-panel-tickets-315683276177?keep_tld=1)

guided hackathon-like sessions that put domain scientists and power grid engineers into small working groups with data scientists to build prototype solutions for the gaps.

Below is a synthesis of a few of the projects that our discussion suggested are needs and that are poised for immediate progress. The 'Expertise Needed' is a guide for the composition of groups that might take up these projects. These are not exhaustive, and these projects are being identified, refined, evolved by the community.

- Integration of power grid data into KnowWhereGraph
  - Cogan Shimizu shared the remarkable KWG on April 13. It is the largest geosciences graph in the world and has an ecosystem of exploration and analysis tools around it. It could be powerful to integrate space weather and power grid data and has the potential to allow us to study compounding effects. This group would outline a roadmap to making space weather a part of that graph database
  - Expertise needed: power grid user needs, domain knowledge, semantic engineering, data science
  - Data available: [KWG](#), [Space Weather-to-Power Grid Ontology](#)
- Developing a space weather vocabulary
  - Anna Kelbert has provided resources to geosciences vocabularies (language for describing data and making them FAIR), but those need to be extended to include space weather. This is a vital piece in enabling data integration and doing space weather systems science
  - Expertise needed: semantic engineering, domain knowledge, FAIR data principles
  - Data available: [FAIR data principles](#), [Space Weather-to-Power Grid Ontology](#), [Space Weather Glossary Harmonization Project](#)
- Space Weather Model Output Visualization
  - We have heard repeated statements about the need to improve trust in space weather model output. One way to do so is to improve visualization and interactivity
  - Expertise needed: domain knowledge, data science, data visualization, power grid user needs
  - Data available: [space weather model output from three separate models](#).
- Overlaying Vulnerability Maps
  - We have discussed a number of vulnerabilities this week, including geographic areas due to space weather, grid components due to aging and other issues, and now population and business vulnerabilities. How can we develop a better situational awareness by integrating these vulnerability maps?
  - Expertise needed: data science, domain knowledge, power grid user needs, data visualization
  - Data available: RUNWITHIT's synthetic environment outputs, [Space Weather model output from three separate models](#). [power grid GIC model output](#)
- Enriching the NERC GIC database
  - Mark Olson shared that NERC is releasing a DB of GIC data. What tools for describing, visualizing, and analyzing those data will enrich them?
  - Expertise needed: data science, power grid user needs, data visualization
  - Data available: NERC GIC DB

- Uncertainty Quantification of Space Weather
  - We have discussed the need to move from deterministic to probabilistic models of space weather for products delivered to the power grid. What are the approaches to calculating uncertainty of those models?
  - Expertise needed: domain knowledge, data science, statistics
  - Data available: [space weather model output from three separate models. Database of Community Coordinated Modeling Center \(CCMC\)](#)
- Space Weather Model Validation
  - We have three space weather model outputs for two storms: Halloween 2003 and 2012 near-miss (did not actually hit Earth). Each model outputs dBh and dB/dt. We have available magnetometer data (SuperMAG) that provides dBh and dB/dt, too. How can we validate these models?
  - Expertise needed: domain knowledge, data science, data visualization, power grid user needs
  - Data available: [space weather model output from three separate models. SuperMAG](#)
- Natural Language Processing of Space Weather Policy Documents and Reports to Identify Trends
  - We heard on April 13 about the myriad agency programs working on space weather. There is a need to better understand the trends, commonalities, distinctions between those efforts (particularly with respect to the power grid). Can we use NLP to examine those documents and discover trends?
  - Expertise needed: data science, machine learning, domain knowledge
  - Data available: [Zotero library](#). Public reports and policies, [Federal Operating Concept for Impending Space Weather Events](#) (mentioned by Kenyetta) + [Power Outage Incident Annex](#)
  - visual of the Software Functions Ontology [https://service.tib.eu/webvowl/#opts=doc=0;cd=10;dd=40;mode\\_compact=true;m\\_ode\\_multiColor=true;#iri=http://cor.esipfed.org/ont/earthcube/sfo](https://service.tib.eu/webvowl/#opts=doc=0;cd=10;dd=40;mode_compact=true;m_ode_multiColor=true;#iri=http://cor.esipfed.org/ont/earthcube/sfo), Prototype <https://github.com/earthcubearchitecture-ecresourcereg/infomodel>
- Prepare a geoelectric field data visualization and inspection system
  - The translation from space weather to the power grid occurs via the geoelectric field (Emanuel Bernabeu emphasized that space weather must provide V/km). The space weather community produces geoelectric field output, but how do we visualize and facilitate interaction with them?
  - Expertise needed: domain knowledge, data science, data visualization, power grid user needs
  - Data available: geoelectric field output [from NOAA](#) and [from Greg Lucas, bezpy](#)
- Map vulnerabilities in communities across the US, producing models that prioritize the minimization of loss of life, and take into account the needs and capabilities of communities to withstand the loss of power
  - It is crucial to be cognizant that this workshop and the entirety of the project and endeavor is primarily meant for the protection of the public. While temporarily losing power is an inconvenience to some, it is a matter of life and death for others.



It is my understanding that in the event of a partial loss of power in the grid, any remaining electricity production is distributed to the grid in a “rolling black out” fashion to minimize the duration in which a single community remains continuously without power. Following discussions with power grid operators during the event, it is apparent that this process is not optimized to minimize loss of life, and does not take into account any information regarding the vulnerability of different segments of the population or their dependence on electricity for survival. An emergent project that should involve data scientists, power grid operators, and relevant government entities, is to map the vulnerability in communities across the US and develop a new model for such events to primarily prioritize the minimization of loss of life and take into account the needs and capabilities of communities to withstand the loss of power. While such a process is relevant to the space weather resilience planning, it further transcends this topic to include the eventuality of loss of power due to any potential circumstance.

- Data available: RUNWITHIT's (RWI) synthetic environment output, [Space Weather model output from three separate models](#). [power grid GIC model output](#)
  - Expertise needed: data scientists, power grid operators, and relevant government entities
- Justify and create artificial intelligence/machine learning (AI/ML)-based models that can be deployed for situational awareness, predictive, and decision-making across the space weather and power grid systems
  - AI/ML may play an important role in power grid situational awareness, mitigative action, and decision-making
  - The physical mechanism of GMD/GIC needs to be further identified and modeled using real and synthetic data. Physical-informed neural networks (PINNs) is a promising approach
  - An under-addressed requirement for the use of AI/ML models to serve a resilient power grid is the susceptibility to cyber attack. This is particularly important for power grid applications
  - Data available: [Solar Dynamics Observatory](#)
  - Expertise needed: data science, artificial intelligence, cyber security, power grid operation and decision-making
  - References [Threat of Adversarial Attacks on Deep Learning](#)
- Produce AI/ML-based uncertainty models for space weather events
  - A constant and recurring gap and wishlist item that emerged from the workshop was the need to include uncertainties in the modelling and reporting of forecasted events to power grid operators as well as the public in the eventuality of the need for preparation. This task together with the conversion of reports from models to volts/km can be accomplished without introducing any changes to the current numerical models of space weather events. If data on the volts/km distribution and duration from various weather events can be obtained, probabilistic machine learning models (either through ensembles or statistical sampling) can be trained to predict the spatial and temporal distribution of volts/km values from the outputs



of the current space weather models to produce the output needed by the power grid operators together with their uncertainties.

- Data available: RUNWITHIT's (RWI) synthetic environment output, [Space Weather model output from three separate models](#). [power grid GIC model output](#)
- Expertise needed: data science, artificial intelligence, power grid operation and decision-making

## Appendix C: Wishlists Across the Sun-to-Power Grid Information Flow

Below are wishlists (specific and important asks) for each link in the Sun-to-Power Grid information flow diagram that was revised during the workshop (see Figure 2). These are actionable places for interaction, translation, exchange, and meaningful collaboration between entities in the system. During the workshop we most extensively defined the wishlists between space weather and the power grid, between regulatory bodies and the power grid, and between the public and the government entities and space weather. Those wishlists are better outlined below, but we make comment on each link in the updated information flow diagram that will guide all potential interactions across this community. Responding to the recommendation above that user engagement activities across the space weather community need to be better aligned and connected, we acknowledge that a complete landscape analysis is needed to complete these wishlists so that they best serve the community. We encourage all groups to contribute their knowledge and research to uncover wishlist items and for these lists to be living conversations.

Figure 4 shows how each wishlist should be interpreted. This highlights the arrow from the power grid to space weather and reveals the power grid asks of the space weather community ('Power Grid to Space Weather').

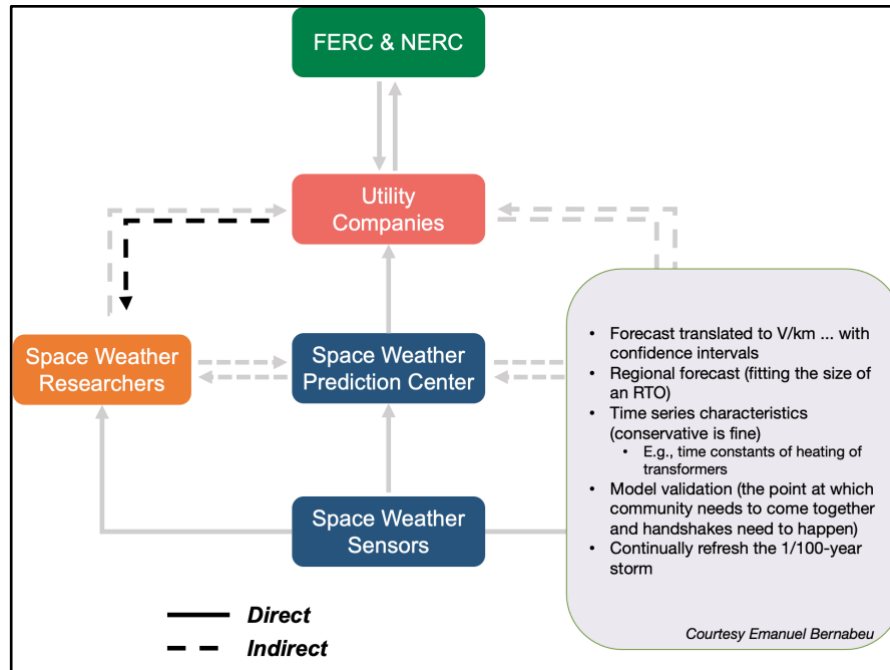


Figure 4: Power Grid to Space Weather Researchers wishlist visualized on the information flow diagram that was refined during the workshop.

## Power Grid to Space Weather Researchers/SWPC

- Emanuel Bernabeu
  - Power Grid-to-Space Weather wishlist/gaps list
    - Forecast translated to V/km, together with providing a measure of the probability of impact (preferably as confidence intervals) with regard to spatial extent, impact intensity, arrival time, and duration of event
      - Can plug this into their models
    - Regional forecast (fits the size of PJM)
    - Time series characteristics (conservative is fine)
      - E.g., time constants of heating of transformers
    - Model validation (the point at which community needs to come together and handshakes need to happen)
    - Continually refresh the 1/100-year storm
      - Start with TPL007 to understand how it is represented (e.g., V/km)
      - Identify localized hot spots based on the storm conditions
      - Understand and quantify the time series signatures that represent the space weather conditions (scaling of historic storms is not sufficient)
  - Become familiar with planning studies utilities are mandated to conduct, which are the processes through which utilities identify vulnerable assets
  - Provide information for two distinct circumstances:
    - Real-time

- Provide real-time and validated data to support system vulnerability assessments
- Help attribute observed effects on the grid to space weather
- Predictive/Warning/Alert
  - Geoelectric field predictions for proactive identification of potential reactive power loss and voltage collapse and subsequent posturing of the system
  - Predictions that permit monitoring the evolution of a storm
- Revise and enhance the granularity of the space weather scales and indices both in terms spatial resolution and intensity (e.g., G5 as the intense level is not granular enough)
  - The major goal: produce a map that provides information on the expected level of activity for a given region
  - Provide statistics alongside Kp-warnings that characterize how the anticipated Kp-value has translated to different E-fields in the past, effectively providing a regional adjustment index based on the historical record of observed values [*Abt Associates*, 2019]
- Support flexible data delivery
- Provide a searchable, easy-to-navigate list of historical events

## Space Weather Researchers/SWPC to Power Grid

- Define in specific terms the products from the research side (in terms of V/km) that are available from models now that are used and useful
  - Define spatial and temporal scales
- Define the point of granularity at which information is no longer used and useful by power grid utilities (e.g., What resolution spatially? What direction resolution of geoelectric field?)
- **Create and sustain an active working relationship** so that we can feed V/km and they can give us GIC data/validation so we can validate our products actively
  - Way to create more fluid feedback
  - Way to continue the conversations like those we had at this workshop
  - Run sim games more often (iterate the process from this workshop; more time for discussion, etc.); would be more valuable with each instance (we had to spend a ton of time and energy to change our own mental paradigms. Next time we would be more open, cognitively, to respond more completely)
- Provide output measurements (e.g., GIC) that enable an information theoretic approach to describe which space weather observables/model parameters provide most information content to geoelectric field and power grid impact
  - Relationship to uncertainty quantification
  - Connect geoelectric field values to their impacts on the grid (requires power grid network models): harmonic propagation through the system; reactive power; transformer heating

- Provide feedback on the language you prefer/understand from space weather side
- Provide the organizational hierarchy of the power grid sector along with guidance on how we can/should interact with each level (e.g., with what information)
  - Provide points of contact for each different level
  - Provide guidance on the most appropriate and clear ways to communicate with each level
  - Help us know what the **operators** (not necessarily high-level individuals) need to know and what they pay attention to (closer interaction with those individuals)
- Invite us to your technical conferences, workshops, and meetings
  - Best example so far: EPRI Sunburst Project
  - Previously: NERC Geomagnetic Disturbance Task Force
  - Invite space weather researchers and forecasters to provide input on the future directions of e.g., NERC efforts
- (utility-specific) Communicate to us what your level of interest/concern/need is in GIC/GMD
  - Help us create one-on-one interactions (individual researcher/research group to single power grid utility)

## Space Weather/SWPC to Space Weather Sensors

- Provide data in the locations that reduce uncertainty in data assimilative physics-based models
  - Complete a robust, real-time, magnetometer network across the US and interconnect the US network to international networks
- Crossing the satellite-to-ground barrier of information and measurements is needed to understand the kinds of sensors that would assist scientists, engineers, and the power industry. Such an endeavor requires joint NSF, NASA, NERC, academics, industry, and all stakeholders to prioritize the continuation of this workshop and maintaining this convergent community.

## Space Weather Researchers/SWPC to DOE

- Provide a 'playground' grid environment to inject currents and validate power grid models (solidify handshake between space weather and power grid communities)
  - Computational environment that acts as a collaborative space for data sharing and collective analysis

- Help us develop computational infrastructure that can more capably allow us to explore the high-dimensional model space (space weather models and parameters and calculated all the way through power grid models; explore more of the possible extreme weather conditions space and to create a DB that can be used to drive and validate power grid GIC models)

**Forthcoming wishlists:** Power Grid to/from Regulatory Bodies (FERC/NERC); DOE to Space Weather Researchers/SWPC, Space Weather SWPC to Researchers

In discussions of the wishlists, a new entity was introduced to the diagram: the public. It is an open question as to which entities the public is connected to and what information flows between them.

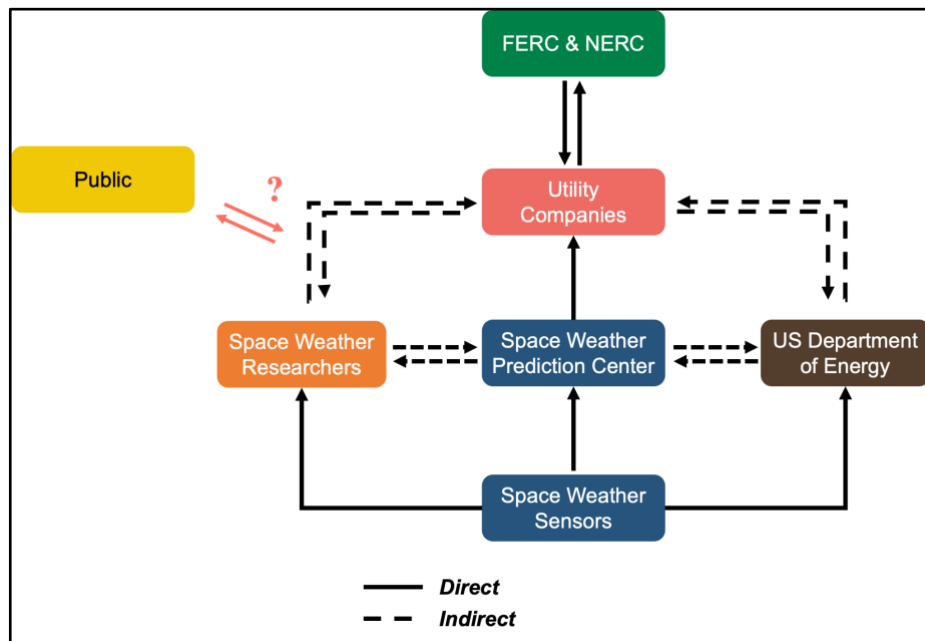


Figure 5: The information flow diagram remains incomplete and requires continual update. The next piece to address is the integration of the public.

Though this is an ongoing discussion, we offer some thoughts from the workshop on this new link to and from the public.

## Public to Power Grid and Space Weather Researchers/SWPC

- Overlay business and population models on space weather hazard and power grid vulnerability maps to determine the socioeconomic impact of a space weather event
- Include the public in the information flow diagram and communication considerations
  - Which box does the arrow from diagram to public flow from?

- FEMA/NERC
- From space weather researchers it is a tenuous arrow (not different/more accessible/digestible dissemination)
- Stop considering the public as monolithic entity
  - Attempt to understand the interests and needs of different groups as well as the asymmetries in vulnerability and impact across the public
- Help us understand your workshops, meetings, conferences by creating accessible dissemination of outcomes
  - Involve journalists in your events
  - Disseminate in novel ways (e.g., beyond journal publications); Social media, podcasts, blogs, public briefings

According to all involved, the most important item needed is the continuation of the openness of the communication channels that cut across all disciplines, from scientists and engineers, to government and industry alike. Feedback from this workshop, and many to be held in the future between all entities, is needed in order to support the takeaways regarding Research-to-Operations and Operations-to-Research (R2O2R) with the involvement of all relevant agencies. This would allow for priorities to be re-examined on a constant basis, with user engagement being maintained throughout.

## Appendix D: Participants

[https://docs.google.com/spreadsheets/d/1LCjhH1Pa\\_ssF2KxzRKnn9CfJcx05QT0/edit?usp=sharing&oid=105532326256950817185&rtpof=true&sd=true](https://docs.google.com/spreadsheets/d/1LCjhH1Pa_ssF2KxzRKnn9CfJcx05QT0/edit?usp=sharing&oid=105532326256950817185&rtpof=true&sd=true)

# Appendix E: Agenda

<https://docs.google.com/document/d/1ym0FVYTeo0bRWi7z9iiylgWQGpMKqdtJ14oXLzxju2c/edit?usp=sharing>