US-European Joint NSF Workshop

FLEXIBLE ELECTRIC GRID CRITICAL INFRASTRUCTURE FOR RESILIENT SOCIETY

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Final Report

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Executive Summary

This report summarizes discussions and recommendations from the NSF-sponsored Joint US-European Workshop titled *"Flexible Electric Grid Critical Infrastructure for Resilient Society,"* held in Philadelphia, PA, USA, on April 21-22, 2023. The workshop was attended by over 70 participants, with roughly 30 attending online. Over 50 participants from the US were supported by the NSF travel grant, Award #ECCS-2312684.

The Workshop topics selected by the Organizing Committee were as follows:

1. The decision and control fundamentals for improved grid reliability and resilience
2. ML/AI data modeling methods and computational advances for flexible grids
3. Social, behavioral, and economic science synergy with the electric grid transformation
4. The impact of weather hazards on the grid and risk assessment and mitigation
5. Complex interactions between the electric grid and other critical infrastructure
6. The education and training fundamentals for the realization and support of a resilient society

The Workshop organizational details – The workshop goals and objectives and the individuals from the Organizing and Steering committee from the US and Europe are provided in the introduction. Each section of the report that covered discussions on the respective topic contains a brief summary of the points raised by the presenters and identifies research gaps, barriers, and desired outcomes. A brief summary of the proposed research directions for each topic is given next.

Topic 1: "The decision and control fundamentals for improved grid reliability and resilience" discussions **(Section 2**) pointed to several major research needs: (a) design new control frameworks and architectures for aggregated DERs to provide market services (e.g., frequency regulation), (b) develop decision and control algorithms to optimize DER resources, including developing methods that can accommodate uncertainties and work for nonconvex models, (c) enhance coordination/cooperation with the bulk grid to improve hosting capacity and flexibility, (d) develop standard interoperable converter controls to address complex interactions that occur over timescales from millisecond to seconds, (e) develop systematic understanding of the ways in which inverter-based sources influence small- and large-disturbance stability, at both local and global grid scales, and determine conditions under which time-domain modeling of the network is necessary and when phasor-based modeling is acceptable, (f) develop numerically robust simulation platforms that are suited to the nonlinear, non-smooth, wide time-scale nature of power systems with inverter-based sources, (g) develop resilience frameworks that address the possibility of rare events yet balance cost versus reliability, and develop resilience metrics with respect to extreme events, (h) design fault/attack monitoring and control algorithms that consider fault/attack propagation and handle heterogenous data, (i) understand relationships between online assessment methods and offline analysis methods, and the impact of model accuracy/uncertainty.

Topic 2: "Machine Learning/Artificial Intelligence (ML/AI) data modeling method and computational advances for flexible grids" discussions (**Section 3**) highlighted several research areas that require further investigation: (a) establishing robust ML methods to address adversarial attacks or data poisoning, biases and peculiarities in the data, and privacy concerns; (b) implementing physics-informed learning for critical systems to enhance reliability and robustness and advance the maturity of ML through extensive demonstrations; (c) developing tools that can handle large-scale, real-world data with varying levels of missing data, varying data quality, and extreme events, and leveraging social media to improve the quality of ML; and (d) combining ML with other methods to achieve more advanced heuristics and improved outcomes.

Topic 3: "Social, behavioral, and economic science synergy with the electric grid transformation" discussions (**Section 4**) explored key research areas/questions, including (a) the need to design DR programs to harness the diversity of communities to support grid reliability and resilience, (b) research focus should systematically incorporate energy justice (defined using the White House Justice40 initiative)

into power systems research, e.g., expansion planning and equitable incentives; (c) Develop methods and approaches to close the gap in clean energy sector jobs and green energy plans between established and emerging/developing economies. (d) modeling the rationality, preference, and flexibility of end-user demand is required for the green energy transition; (e) the need to educate end users on their energy profiles and develop proper incentives and awareness to understand what clean energy is and the energy transition fully; and (f) power researchers need to use outputs from social science research to drive proper indices and decision making.

Topic 4: "The Impact of Weather Hazards on the Grid and Risk Assessment and Mitigation" discussions (**Section 5**) emphasized several research areas that need further exploration: (a) establishing tools and mechanisms to leverage engineering principles and network/data science models for informed risk assessment and mitigation in power systems, considering power system interdependence with lifeline networks, (b) establishing tools and mechanisms that leverage the untapped potential in big data analytics for spatiotemporal outage risk predictions (indexed with both location and volume) and risk-informed decision-making for emergencies, and (c) establishing effective market and policy instruments for multi-hazard risk managemnet in power systems capturing cumulative impacts of events, diverse risk attitudes, and action timelines.

Topic 5: "Complex interactions between the electric grid and other critical infrastructures" discussions (***Section 6***) lead to some of the key suggested research directions: (a) Interactions between hydrogen and electric energy systems, going beyond just technical feasibility to also consider the economics of the integrated solutions, (b) Analyses and optimizations of broader multi-energy systems such as using different time scales for modeling various sub-systems within the interconnected energy systems, examining value quantification of integrated energy, and integrating customer behavior into the analysis, (c) inclusion of uncertainty (especially deep uncertainty) in multi-energy system analysis and compounded threat analysis for multi-energy system analysis, and (d) address reduction of CO2 in steel and chemical industries as they are some of the hardest to decarbonize.

Topic 6: "The education and training fundamentals for the realization and support of a resilient society" discussions (***Section 7***) informed that: (a) twelve power system operators have identified prioritized topics for the teaching agenda based on their needs (https://globalpst.org/category/pillar/pillar-3/, (b) professional education programs are appealing to students due to the high expected earnings and lower tuition fees, particularly in community colleges, (c) Students appreciate a blend of theoretical and skill-development courses, particularly hands-on application courses in the laboratory, (d) in addition to technical skills, transversal, business, and green skills are crucial in the energy sector. Soft skills, innovation, and entrepreneurship experience are highly desirable, (e) educating students from a young age about energy systems can increase awareness and engagement in the field, (f) physical hardware-in-the-loop (HIL) simulation, remote or virtual labs, and interactive tools like Jupyter notebooks are seen as efficient and promising educational tools, but there is a need to adapt tools and methodologies to the features of the learner target group, (g) bringing professionals from the industry, such as utilities and public service commissions, into the classroom can greatly motivate students and (h) establishing an interdisciplinary energy institute can engage the wider community within the university and attract master's students from different backgrounds, (i) increasing the rate of adoption of open-source tools could facilitate worldwide research advancement progress in the developing countries.

The report concludes with **Section 8** – "Future steps," stating that the experience from the joint US-European Workshop has shown some commonalities and some differences in the approaches –future workshops should be held to explore the synergies further. Further, based on the result of these workshops, it is clear that the report may be useful as a Research Roadmap in the future.

The report's appendices contain the Workshop program, the list of participants, and a record of the discussions taken by the faculty scribes that volunteered to capture the discussion points.

Introduction

1.1. Background

The electric grid critical infrastructure is transforming from concentrated carbon-intensive legacy generation options to renewables in the form of distributed energy resources (DERs), often connected through inverters. One characteristic of renewable energy is its uncertainty, which requires additional planning and operating challenges not traditionally faced with the system of the past. While this transformation aims at the net-zero carbon grid targets, the impact of such electric grid developments on other critical infrastructures needs to be carefully considered – so that the overall effect strengthens the resilience not only of the electric grid – but also of each dependent critical infrastructure such as water, transportation, telecommunication, energy carriers, etc. The Federal Energy Regulatory Commission (FERC) Order 2222 in the (United States (U.S.) has paved the way for DER owners and aggregators to work with utility and market operators to achieve the reliable and safe operation of an integrated grid. In addition, extreme weather events, and its impacts on the electric grid operation are also becoming more prevalent focus going forward requiring that such weather impacts be taken into consideration in the various planning studies. A similar regulatory framework has been focused on grid development in Europe for quite some time, and a variety of demonstration projects have been undertaken over the last decade. The Workshop's goal was to bring together researchers, industry stakeholders, and government representatives to explore how the grid transformation may affect grid flexibility and its ability to serve other critical infrastructures to ensure a resilient society. The objective is to continue the discussion from the prior NSF-sponsored Workshops held in the US in 2020 and 2021, and jointly with the European partners in Europe in 2022, attended by over 100 researchers from well over 50 US/European academic, government and industry organizations – to further grid resilience discoveries and strategies through the proposed Workshop with the participation of a wider scientific community.

This US-European Workshop was focused on exploring five scientific areas: (1) Data and physics-based modeling to discover new fundamentals in deep-learning approaches, (2) Transformational electric grid distributed control strategies laying the foundation for a resilient net-zero grid of the future, (3) Synergies between social, behavioral, and economic sciences to assess a human aspect of grid modernization leading to new models for electricity markets and incentives, (4) Scalability of cybersecurity and privacy requirements across millions of internet-of-things consumers of energy services opening new questions on how to model and mitigate the risk of loss of trustworthiness, and (5) Cross-dependency between electric grid infrastructure and other critical infrastructures discovering how the complex system model formulations and dynamics interact, and (6) How to develop science, technology, engineering, and mathematics (STEM) content for informing and engaging the public, and education and training of kindergarten to twelfth grade (K-12) students and early-carrier professionals.

The international experience of interacting with peers from over 20 universities from a dozen leading European countries was invaluable for the US participants in forming a broader social, cultural, and political understanding of grid modernization. To benefit from diverse approaches to grid modernization, US researchers from over 40 universities engaged with their European counterparts to exchange research experiences. This final report informs the public about the importance of critical infrastructure interactions and the impacts of electric grid resilience on other critical infrastructures serving essential societal needs. This Workshop, with over 70 participants, contributed to the training and research awareness of the younger professors and students from the participating universities, industry, and government organizations to prepare them to better serve the societal needs for resilient infrastructures of the future.

The Workshop discussion aimed at defining the needs of the future grid stakeholders, including market, utility, and DER operators, and focused on defining research directions, questions, gaps, and barriers.

Workshop discussion topics are listed below:

1. The decision and control fundamentals for improved grid reliability and resilience

2. ML/AI data modeling method and computational advances for flexible grids
3. Social, behavioral, and economic science synergy with the electric grid transformation
4. The impact of weather hazards on the grid and risk assessment and mitigation
5. Complex interactions between the electric grid and other critical infrastructure
6. The education and training fundamentals for the realization and support of a resilient society

1.2. Organizational Details

Workshop Agenda:

<u>Day 1</u>

1. The decision and control fundamentals for improved grid reliability and resilience
2. ML/AI data modeling method and computational advances for flexible grid
3. Social, behavioral, and economic science synergy with the electric grid transformation

The impact of weather hazards on the grid and risk assessment and mitigation

<u>Day 2</u>

4. Complex interactions between the electric grid and other critical infrastructures

The education and training fundamentals for the realization and support of a resilient society

Workshop Format

From the experience from recent workshops on a different aspect of a similar topic, we adopted the following format for each of the proposed discussion sessions:

- Sessions lasted 1-hour and 45minutes, and there were two sessions in the morning and afternoon of April 21, 2023, and one in the morning of April 22, 2023
- Sessions had two opening talks, each 10 minutes long, from the US and two from Europe, one on the scientific, and the other on the practical aspects of the selected topic from each region
- Each session had two moderators, one moderating the speakers and the other moderating the Q/A, which took around one hour in each session

Invited Speakers

<u>Opening Keynote</u>**,** Daniel Kushner, Director of Resiliency Strategy, Luma, Puerto Rico

<u>Lunch Keynote</u>, James Glotfelty, PUC Commissioner, TEXAS PUC

NSF Support: Travel Grant for the participants from the USA (30 in-person and 13 online attendees)

Workshop Host: Temple University, Philadelphia, PA

Date and Location: Temple University Conference Center, April 21-22, 2023, Philadelphia, PA

Attendance: 36 Moderators/Speakers and over 70 attendees from academia/ industry/ government, all by Invitation only

Sponsorship: National Science Foundation-NSF, Texas A&M University and Temple University

<u>Organizing Committee</u>:

US side: M. Kezunovic (Co-Chair), Texas A&M University; A. Chakrabortty (NSF Coordinator); Z. Obradovic, Temple University; M. Almassalkhi University of Vermont; K. Baker, University of Colorado Boulder; I. Hiskens University of Michigan; B. Kroposki NREL; K. Tomsovic, University of Tennessee; M. McGranaghan, Electric Power Research Institute

European side: L. O. Camacho, Pontificia Comillas University, Spain; J. P. Lopes Porto University, Portugal; L. Nordström KTH-Royal Institute of Technology, Sweden; M. M. Polycarpou University of Cyprus, Cyprus; D. Strauss-Mincu Fraunhofer IEEE, Germany; P. Taylor University of Bristol, UK

Outcome: Joint US/European Report

Workshop registration fee: $150 for in-person and online participation

2. Topic 1: The Decision and Control Fundamentals for Improved Grid Reliability and Resilience

2.1. Presenters' Emphasis

The theme in this section is the control challenges and opportunities associated with DERs:

- DERs need to be studied across multiple dimensions: (1) load management; (2) dynamic interactions among the DERs themselves and with the bulk grid; (3) reliability, especially when EVs and thermostatically controllable loads are present; and (4) integration with markets.
- Grids with DERs are complex dynamical systems that are: (1) decentralized, (2) heterogeneous, (3) large-scale with many devices, (4) nonlinear, non-smooth, and multi-timescale, and (5) temporally coupled if storage elements are present.
- Grid resilience: weather-driven events, such as wildfires and events synchronizing the response of large numbers of DERs, require new thinking about resilience. Appropriate resilience metrics are not yet clear.
- Monitoring and fault diagnoses: rather than the current manual-setting process, relays addressing fault analysis, fault postmortem assessment needs to be set more autonomously. Challenges arise due to the scale of the system, software/hardware interconnections, and uncertainties in the system parameters.
- Controlling DERs in the presence of model uncertainty: most sophisticated methods require parameters that are not readily known, may rapidly change based on the operating point and environmental conditions, and need to be estimated online.

2.2. Research Area Suggestions

The workshop presenters and attendees have made the following research suggestions:

- Design new control frameworks and architectures for aggregated DERs to provide committeed market ancillary services (e.g., frequency regulation).
- Develop decision and control algorithms to optimize DER resources, including developing methods that can accommodate uncertainties and work for nonlinear and nonconvex models.
- Enhance coordination/cooperation with the bulk grid to improve hosting capacity and flexibility.
- Develop standard interoperable converter controls to address complex interactions on timescales from milliseconds to seconds.
- Develop a systematic understanding of how inverter-based sources influence small- and large-disturbance stability at local and global grid scales. Determine conditions under which time-domain modeling of the network is necessary and when phasor-based modeling is acceptable.
- Develop numerically robust simulation platforms suited to the nonlinear, non-smooth, wide time-scale nature of power systems with inverter-based sources.
- Develop resilience frameworks that address the possibility of rare events yet balance cost versus reliability/resilience. Develop resilience metrics for extreme events.

- Design fault/attack monitoring and control algorithms considering fault/cyber-attack propagation and handling heterogeneous data.
- Understand relationships between online assessment and offline analysis methods and the impact of model accuracy/uncertainty.

2.3. Gaps, Barriers, and Desired Outcomes

Several approaches have been proposed for decision and control strategies to improve grid reliability and resilience, in terms of aggregate DER control to support grid services; grid-forming control schemes that support power-electronic dominated power grids and address instability issues; distributed fault diagnoses of interconnected cyber-physical systems; and online learning methods and using heterogeneous(parameter estimation) methods that utilize heterogenous data to address model uncertainty.

- Fundamental and practical gaps have been identified: (1) scalability of algorithms for assessing dynamic performance; (2) practical implementation challenges; (3) better monitoring and action to manage system assessment of faults; and (4) dealing with system uncertainty.
- The scalability of system analysis tools and related coordination algorithms were mentioned and discussed several times as important barriers. In a heterogeneous system, the dynamic behavior of power-electronic converters may introduce fundamental constraints. Even though real-time controls of power electronic interfaces are decentralized, accounting for all the detailed dynamics can result in an intractable analysis problem. A balance between model detail and tractability, as well as the role of centralized and distributed controls, need to be carefully considered explicitly account for scalability in both device- and system-level control architectures.
- The desired outcome is a resilient and reliable grid that can leverage the new technological capabilities introduced by DERs.

3. Topic 2: ML/AI Data Modeling Method and Computational Advances for Flexible Grids

3.1. Presenters' Emphasis

The theme of the presentations in this panel was geared toward the unparalleled challenges in (1) developing ML techniques for short-term optimal control, long-term planning, decision support, and security enhancement against attacks or major failures in smart grids, which take into account the possibility of varying topology, virtual sensor and observability, spatiotemporal data with non-stationary critical properties, and human involvement; (2) combining ML and classical optimization control methods to find implementable solutions while maintaining robustness and reliability through the use of underlying physics for near real-time applications on the cyber-physical power systems, (3) quantifying modeling uncertainties of buildings through the integration of data-driven models with domain knowledge to achieve more robust probabilistic results and enhancing system controls for more precise management, and 4) developing new protocols for transferring data from various sources with anonymized and scarce information, low precision, inconsistent labels, small effect sizes, and noisy observations and understanding the precursors of specific events from a ML perspective.

3.2. Research Area Suggestions

The panel presentations and ensuing discussions highlighted several research areas that require further investigation. Research should focus on (1) establishing robust ML methods to address adversarial attacks or data poisoning, biases and peculiarities in the data, and privacy concerns; (2) implementing physics-informed learning for critical systems to enhance reliability and robustness and advance the maturity of ML through extensive demonstrations; (3) developing tools that can handle large-scale, real-world data with varying levels of missing data, varying data quality, and extreme events, and leveraging social media to improve the quality of ML; and (4) combining ML with other methods to achieve more advanced heuristics and improved outcomes.

3.3. Gaps, Barriers, and Desired Outcomes

The state-of-the-art research has provided many interesting works on ML-enabled modeling, analysis, control, etc. Future research should not reinvent the wheels but complement existing knowledge. The panel presentations and the discussions identified several gaps, barriers, and desired outcomes as follows:

- The absence of mechanisms to integrate physical knowledge into ML models is a significant issue that needs to be addressed. Improving algorithms to incorporate domain-specific knowledge and real-world constraints is crucial but currently lacking. Scaling up ML models is also challenging. While building a model with ten nodes representing ten sensor points may be straightforward, expanding to 100 nodes can be difficult in terms of training and inference, resulting in longer processing times. Furthermore, data-driven models are challenging to apply in optimization techniques because they tend to favor simpler models over complex ones.
- Understanding customers is vital, as there may be a disconnect between ML development and utility applications. Challenges arise when implementing solutions in practice, as demonstrated in the medical field, where precision and certainty are critical. Developing additional tools to visually communicate reasoning can help bridge the gap between ML and practitioners; however, it is challenging.
- Incorporating uncertainty into the modeling process, particularly in communications, can be a daunting task. Although several decision-making and optimization methods are available, the choice of approach depends on the nature of the uncertainty and the specific application.

4. Topic 3: Social, Behavioral, and Economic Science Synergy with the Electric Grid Transformation

4.1. Presenters' Emphasis

Panelists in this session focused on integrating social science research to equitably unlock the role of electric demand towards a resilient, climate-neutral, and sustainable grid. The high-level topics discussed included: (1) designing targeted demand response (DR) programs based on the differences in the community, (2) making a concerted effort to include energy justice and social science in the power systems research agenda, (3) discussing the role of sustainable development goals (SDGs) in the European efforts for a sustainable, climate neutral, and resilient grid, and (4) highlighting the need for harnessing the electric demand for the electric grid transition.

4.2. Research Area Suggestions

Panel presentations, audience questions, and the moderated discussion landed on some key research areas/questions, including: (1) the need to design DR programs to harness the diversity of communities to support grid reliability and resilience; (2) research focus should systematically incorporate energy justice (defined using the White House Justice40 initiative) into power systems research, e.g., expansion planning and equitable incentives; (3) Develop methods and approaches to close the gap in clean energy sector jobs and green energy plans between established and emerging/developing economies; (4) modeling the rationality, preference, and flexibility of end user demand is required for the green energy transition; (5) the need to educate end users on their energy profiles and develop proper incentives and awareness to fully understand what is clean energy and the energy transition; and (6) power researchers need to use outputs in social science research to drive proper indices and decision making.

4.3. Gaps, Barriers, and Desired Outcomes

In unlocking the electric grid transformation to a green energy future using social, behavioral, and economic sciences integrated with power systems research, the following gaps and barriers were discussed and identified by the presenters and audience:

- There is a lack of awareness by end-users in topics such as energy literacy: most people do not know what their largest energy users are, so how do they know which user to target to save money? There is a need to educate the community on available programs, highlight the value proposition for the end user, and provide information that participating is aligned with their goals for local electricity resilience.
- Policies and programs (e.g., DR) need to be properly designed to extract the maximum amount of grid flexibility equitably. Demand is quite heterogeneous; one-size-fits-all DR programs are not sufficient.
- A large segment of the population does care about climate change, but when compared to the short-term electric rates, reliability, extreme weather, etc., they do not make a connection. Concomitantly, there is a lack of trust between the community and the electric utility. Trust and education of the electric grid should be championed from within by trusted community members, who are part of the solution, rather than imposing policies and actions on them.
- Power systems researchers and social science researchers are concerned about similar topics but use different language/terms to describe the same phenomena. It is a necessity that both groups work together to develop a common set of metrics and keywords to link research across the domains and push cross-disciplinary initiatives.

5. Topic 4: The Impact of Weather Hazards on the Grid and Risk Assessment and Mitigation

5.1. Presenters' Emphasis

The panelists' discussions focused on the unprecedented challenges of resilience in critical infrastructure and presented potential solutions to address those challenges. Risk management in the power sector has always been complex. Hence, some challenges are long standing, while others are caused by changes in power systems and environment. The transformation of power systems and change of climate complicate identification of weather hazards. Long-standing issues with estimation of value of lost load and multi-stakeholder perspectives challenge risk assessment. The panelists discussed several main challenges:

- Climate change and variability impacting the operation of critical infrastructure: The infrastructure adaptation to climate change is urgently needed, and research domains such as earth sciences, data sciences, and explainable AI could help facilitate this adaptation by translating global climate models to stakeholder needs and scales, assessing the lifeline networks' risks and providing mitigations.
- The use of evidence from climate science in supporting decision making is a more open area than is often thought.
- Predicting, managing, and mitigating the risks of forced outages: Big data analytics and AI could prescribe solutions, and risk analytics may improve resilience to forced outages.
- The interrelated concepts of risk and resilience in power systems aid in identifying hazardous weather events, assessing weather-induced risks in power systems, and responding to those risks.
- The role of weather simulations: These simulations capture prevailing climate uncertainties, and risk assessments should leverage both historical and synthetic weather databases in energy systems modeling and analysis.

5.2. Research Area Suggestions

The panel presentations and the ensuing discussions suggested several research areas that need further exploration. Research should focus on (1) establishing tools and mechanisms to leverage engineering principles and network/data science models for informed risk assessment and mitigation in power systems considering its interdependence with lifeline networks, (2) establishing tools and mechanisms that leverage the untapped potential in big data analytics for spatiotemporal outage risk predictions (indexed with both location and volume) and risk-informed decision-making for emergencies, and (3) establishing effective market and policy instruments for multi-hazard risk assessments in power systems capturing cumulative impacts of events, diverse risk attitudes, and action timelines.

5.3. Gaps, Barriers, and Desired Outcomes

Despite the national interest in enhancing power grid resilience, the ongoing research on related topics, and the existing state of knowledge, the panel presentations and the discussions identified several gaps, barriers, and desired outcomes as follows:

- The relationship between outage risk indicators and system resilience, which could effectively consider data of different resolutions and decisions of varying granularity requirements at multiple spatial scales, has not been established clearly in the literature.
- The existing literature lacks effective mechanisms for multi-stakeholder engagement in power grid risk management processes when exposed to evolving weather extremes.
- There is a lack of understanding of how hazard, vulnerability, and the resulting damage exposures are linked to environmental justice. There remain open questions on how damage exposure and risk mapping should be carefully conducted to consider individuals and equity and ensure that the risk map is used and decided upon correctly and reasonably at different spatiotemporal scales. New mechanisms on how procedural and distributional equity can be incorporated into risk management processes are in need.
- Linking research outcomes to practice – a notable need is addressing the modeling and solution complexity and scalability. New approaches that can effectively capture this complexity while including (learning and adapting to) the dynamics of the system and the conditions it is exposed to should be investigated.
- An ongoing challenge is the heterogeneity in utility industry practices regarding the available databases for risk management, data acquisition methods, and resolutions.

6. Topic 5: Complex Interactions Between the Electric Grid and Other Critical Infrastructures

6.1. Presenters' Emphasis

This panel focused on complex interactions between the electric grid and other critical infrastructures. The speakers discussed the topic from three perspectives: (1) increasing the power grid flexibility through energy systems integration, (2) re-envisioning resiliency economics for power grids, and (3) examining dependency of the electric grid on other critical infrastructures such as gas, communications, water, and hydrogen systems. The overall assessment of the panel discussion was that it is critically important to analyze interdependent energy systems metioned above together for deep decarbonization and that features such as economic viability and uncertainty must be included in the analysis.

6.2. Research Area Suggestions

- Some of the key research directions suggested during the panel session include: (1) Need to study the interactions between hydrogen and electric energy systems, going beyond just technical feasibility to consider the economics of the integrated solutions as well; (2) Analyses and optimizations of broader multi-energy systems. Specific research suggestions for this area include (i) using different time scales for modeling various sub-systems within the interconnected energy systems, (ii) examining value quantification of integrated energy, and (iii) integrating customer behavior into the analysis; (3) The need for the inclusion of uncertainty (especially deep uncertainty) in multi-energy system analysis was the key theme of one speaker. Compounded threat analysis was also put forth as a desirable feature for multi-energy system analysis; and 4) One speaker noted that some industries are harder to decarbonize than others, and decarbonization of steel and chemical, are considered some of the hardest to decarbonize and is an open research problem.

6.3. Gaps, Barriers, and Desired Outcomes

- GB experience is that sharing data between organisaions/sectors is a key barrier to analysis of interconnected infrastructure systems. Many different interests can apply here, including commercial and security.
- A panel speaker noted that by 2050, 250 GW of energy storage may be required for decarbonization; batteries alone may not meet this requirement. Today, there is a gap in understanding what will fill this need for energy storage beyond batteries and how it would be financially viable.
- Analysis of multi-energy systems was a key theme. The lack of datasets was noted as a key barrier. Currently, comprehensive datasets for multi-energy systems modeling and simulation do not exist. Another barrier is that these current datasets are not updated. Often, academics end up using obsolete datasets for their analysis. A desirable outcome was for the community to build open-source datasets for multi-energy systems that are consistently updated.
- Another noted gap was the lack of (i) economy-wide modeling of multi-energy systems and (ii) inclusion of social behavior into the energy analysis. The final speaker noted that key challenges in the current paradigm of complex and integrated energy systems include integrating and managing advanced digital infrastructures, designing and operating 100% renewable energy with green hydrogen, developing digital models for emerging technologies, and the integrated optimization of multiple networks.
- An audience member bought up battery disposal as a barrier to the large-scale inclusion of batteries.
- Storage and transportation of Hydrogen (H_2) were also discussed as a challenge; importantly, the infrastructure financing for the same was noted as a key barrier today.
- Toward a desirable outcome for the future workforce, there was a discussion on the need for interdisciplinary researchers to tackle future problems in energy systems. Electrical engineers alone cannot solve future energy systems problems.

7. Topic 6: The Education and Training Fundamentals for the Realization and Support of a Resilient Society

7.1. Presenters' Emphasis

Panelists in this session focused on developing STEM educational content to inform and engage the public and educate and train students and early-carrier professionals. The presentations covered:

- The activities of the Pillar 3 of the Global Power System Transformation (G-PST) Consortium facilitate the development of a diverse and inclusive workforce to support deep decarbonization of the electric power sector globally.
- Multiple pathways for building a robust workforce in electric power engineering that features employment preparation education (EPE) and integrate industry support and pipeline courses across high schools, community colleges, and universities (BS, MS, Ph.D.).
- A master's program that focuses on the education and training to create a competent workforce for intelligent critical infrastructure systems, which uses laboratory testbeds to provide practical hands-on training.

- Identifying emerging skill needs and educational tools towards the digital energy transition; Advanced educational methods to support student engagement and learning while providing a meaningful experience.

7.2. Education Area Suggestions

- Some of the key educational directions suggested during the panel session include: (1) twelve power system operators have identified prioritized topics for the teaching agenda based on their needs, which can be found in https://globalpst.org/category/pillar/pillar-3/, (2) professional education programs should, on the paper, be appealing to students due to the high expected earnings and lower tuition fees, particularly in community colleges, (3) students appreciate a blend of theoretical and skill-development courses, particularly hands-on application courses in the laboratory, (4) in addition to technical skills, transversal, business, and green skills are crucial in the energy sector. Soft skills, innovation, and entrepreneurship experience are highly desirable, (5) educating students from a young age about energy systems can increase awareness and engagement in the field, (6) physical hardware-in-the-loop (HIL) simulation, remote or virtual labs, and interactive tools like Jupyter notebooks are seen as efficient and promising educational tools. However, there is a need to adapt the educational tools and methods employed to the target group of learners: young students, undergrads, Ph.D. students, researchers, power sector professionals, and society as a whole, (7) bringing professionals from the industry, such as utilities and public service commissions, into the classroom can greatly motivate students and (8) establishing an interdisciplinary energy institute can engage the wider community within the university and attract master's students from different backgrounds.
- Despite the increased focus on developing open tools and open data sets to share with third research groups worldwide and the industry in the developing world, open tools are barely used by third parties. There is a need to investigate the definition of meaningful approaches to open-source tools (including open data sets) adoption by third parties both in research and within developing world institutions and industries.

7.3. Gaps, Barriers, and Desired Outcomes

- Additional technological tools and new educational methods are needed to facilitate remote or virtual lab support and hybrid education in engineering disciplines. When implementing advanced tools and methodologies, these should be well adapted to the target group of learners. There is a need to investigate the appropriate match between tools, methodologies, and learners groups.
- Key skill gaps identified in power system digitalization include data management and analysis, big data, cybersecurity, and programming and development competencies.
- Due to higher salaries, many electrical engineering (EE) students are interested in switching to computer science (CS). Increasing the salary for power engineers is a solution, but there is a real struggle within regulated industries.
- There is a shortage of power engineers because many people don't realize the importance of the field. Efforts should be made from the early stages of education to help students understand the significance of power systems.
- The industry should define the need of the industry. We need to rethink how we are trying to map what’s happening in the world into the university environment.
- The energy system is an interdisciplinary problem. However, people do not work well across areas. It is necessary to restructure educational systems to facilitate interdisciplinary collaboration from an early age through activities like games and engaging with others.

- There is a need to increase the level of use of open tools and data sets by the research community worldwide and industry in developing countries to accelerate research advancement and the rate of development of these countries.

8. Conclusions

The discussions were quite elaborate and useful in exchanging ideas between the US and European partners, giving enough substantive suggestions for the Research Roadmap this report outlines. It has also been concluded that such interactions should continue in the future since the research focus in the US and Europe while starting from similar problems, has resulted in differences in the research approaches stemming from the specific policy, regulatory and societal circumstances, and historical developments of the electric grid on the two continents.

Appendices:

A. Workshop Program
B. List of Attendees
C. Scribe notes from discussions on Topic 1
D. Scribe notes from discussions on Topic 2
E. Scribe notes from discussions on Topic 3
F. Scribe notes from discussions on Topic 4
G. Scribe notes from discussions on Topic 5
H. Scribe notes from discussions on Topic 6

Appendix A: Workshop Program

“Flexible Electric Grid Critical Infrastructure for Resilient Society”
NSF Joint US-European Workshop
Temple University Center City (TUCC)
1515 Market Street
April 21-22, 2023
Philadelphia, PA
Agenda
All times are ET USA

List of Speakers/Moderators
Table Codes
Designation: “S”-Speaker; “M”-Moderator
Region: (*) from the US; (**) from Europe
Participation: “T”-Travel; “O”-Online

Friday, April 21, 2023

Room 222

8:00 am: Opening Remarks, Mladen Kezunovic, Workshop Chair

8:15 am: Keynote Speaker, Daniel Kushner, Director of Resiliency Strategy, Luma, Puerto Rico

8:45 am: Topic 1-The decision and control fundamentals for improved grid reliability and resilience

Name	**T/O**	**US S#1**	**US S#2**	**US M**	**EU S#1**	**EU S#2**	**EU M**	**Comments**
M. Almassalkhi*(Univ of VT, USA)	T	X						8:45-8:55 am
D. Gross* (U of Wisconsin-Madison, USA)	T		X					8:55-9:05 am
I. Hiskens* (U of Michigan, USA)	T			X				
M. Polycarpou** (U of Cyprus, Cyprus)	T				X			9:05-9:15 am
R. Gupta** (EPFL Switzerland)	O					X		9:15-9:25 am
Nikos Hatziargyriou** (NTUA, Greece, DERLab, Germany)	O						X	
9:25 am: Moderated discussions, Topic 1								
10:25 am-10:45 am: Coffee/Tea Break								

10:45 am: Topic 2-ML/AI data modeling method and computational advances for flexible grids

Name	T/O	**US S#1**	**US S#2**	**US M**	**EU S#1**	**EU S#2**	**EU M**	**Comments**
Z. Obradovic* (Temple, USA)	T	X						10:45-10:55 am
Q. Z. Sun* (Univ. of Central Florida, USA)	T		X					10:55-11:05 am
K. Tomsovic* (U of Tennessee, USA)	T			X				
B. Hammer**(U of Bielefeld, Germany)	O				X			11:05-11:15 am
P. Panciatici** (RTE-France)	O					X		11:15-11:25 am
C. Dent** (Univ. of Edinburgh, and Alan Turing Institute, UK)	T						X	
11:25 am: Moderated discussions, Topic 2								
12:25-1:45 pm: Lunch Break								
12:45-1:15 pm: Lunch Keynote, *J. Glotfelty, PUC Commissioner, TEXAS PUC*								

1:45 pm: Topic 3-Social, behavioral, and economic science synergy with the electric grid transformation

Name	T/O	**US S#1**	**US S#2**	**US M**	**EU S#1**	**EU S#2**	**EU M**	**Comments**
K. Baker*(U of Co-Boulder, USA)	T	X						1:45-1:55 pm
J. Mathieu* (U of Michigan, USA)	T		X					1:55-2:05 pm

R. O'Neill* (ARPA-E, USA)	T			X				
P. Koundouri**(DTU, Denmark and Athens Univ, Greece)	O				X			2:05-2:15 pm
P. Linares** (Comillas, Spain)	O					X		2:15-2:25 pm
L. Nordstrom** (KTH, Sweden)	T						X	
2:25 pm: Moderated discussions, Topic 3								
3:25 pm-3:45 pm: Coffee/Tea Break								
3:45 pm: Topic 4-The impact of weather hazards on the grid and risk assessment and mitigation								
Name	T/O	**US S#1**	**US S#2**	**US M**	**EU S#1**	**EU S#2**	**EU M**	**Comments**
A. R. Ganguly*(Northeastern, USA)	T	X						3:45-3:55 pm
M. Kezunovic* (Texas A&M, USA)	T		X					3:55-4:05 pm
S. M. Trento* (EPRI, USA)	T			X				
E. Spyrou** (Imperial College, UK)	T				X			4:05-4:15 pm
D. Kroeger**(TU Dortmund, Germany)	T					X		4:15-4:25 pm
A. Ulbig** (RWTH Aachen, Germany)	T						X	
4:25 pm: Moderated discussions, Topic 4								
5:25 pm: Adjourn								
7:00 pm: Hosted Dinner-Estia Restaurant, https://estiarestaurant.com/								
Saturday, April 22								
Room 222								
8:30 am: Topic 5-Complex interactions between the electric grid and other critical infrastructures								
Name	T/O	**US S#1**	**US S#2**	**US M**	**EU S#1**	**EU S#2**	**EU M**	**Comments**
B. Kroposki*(NREL, USA)	T	X						8:30-8:40 am
Y. Dvorkin*(John Hopkins, USA)	T		X					8:40-8:50 am
Mark Lauby* (NERC, USA)	T			X				
J. P. Lopes**(INESC, Portugal)	T				X			8:50-9:00 am
P. Taylor**(Bristol, UK)	O					X		9:00-9:10 am
N. Constantinescu** (entso-e, Belgium)	O						X	
9:10 am: Moderated discussions, Topic 5								
10:10 am-10:30 am: Coffee/Tea Break								
10:30 am: Topic 6-The education and training fundamentals for the realization and support of a resilient society								
Name	T/O	**US S#1**	**US S#2**	**US M**	**EU S#1**	**EU S#2**	**EU M**	**Comments**
C. Smith* (ESIG, USA)	T	X						10:30-10:40 am
S. Raju*(U of Minnesota, USA)	T		X					10:40-10:50 am
E. Pistikopoulos*(Texas A&M, USA)	T			X				
M. Michael**(U of Cyprus, Cyprus)	O				X			10:50-11:00 am
A. Chronis** (NTUA, Greece)	O					X		11:00-11:10 am
L. Olmos**(Comillas, Spain)	T						X	
11:10 am: Moderated discussions, Topic 6								
12:10 pm: Adjourn								

Appendix B: List of Attendees

Flexible Electric Grid Critical Infrastructure for Resilient Society **NSF Joint US-European Workshop** **Temple University Conference Center** **April 21-22, 2023** **Philadelphia, PA**					
Notation **T/O:** Travel/online **E/W/C:** Region of the US: East, West, Central **L: Local (from Philly)** **SC#:** Scribe, session number **S/M:** Speaker, Moderator					
US Invited Participants (32)					
Name		**Institution**	**Rank/Title**	**email**	**T/O/Region/ Scribe (SC)**
1.	Maria Ilic	MIT	Professor	ilic@mit.edu	O/East (E)
2.	Chiara Lo Prete	Pen State	Assoc. Prof.	cxl63@psu.edu	T/E
3.	Yan Li	Pen State	Assist. Prof.	yql5925@psu.edu	T/E/SC2
4.	Leigh Tesfatsion	Iowa State	Res. Prof.	tesfatsi@iastate.edu	O/Central (C)
5.	Quanyan Zhu	N.Y. University	Assoc. Prof.	quanyan.zhu@gmail.com	T/E
6.	Masood Parvania	Univ. of Utah	Assoc. Prof.	parvania@gmail.com	O/West (W)
7.	Yuanyuan Shi	UCSD	Assist. Professor	yyshi@eng.ucsd.edu	T/W/SC5
8.	Payman Dehghanian	GWU	Assist. Prof.	payman@email.gwu.edu	T/E/SC4
9.	Timothy Hansen	SD-State Univ.	Assoc. Prof.	timothy.hansen@sdstate.edu	T/C/SC3
10.	Line Roald	Wisconsin-Madison	Assist. Prof.	roald@wisc.edu	O/C
11.	Baosen Zhang	Univ of Washington	Assoc. Prof.	zhangbao@uw.edu	F/W/SC1
12.	Sara Eftekharnejad	Syracuse	Assist. Prof.	seftekha@syr.edu	T/E/SC4
13.	Anamika Dubey	WSU	Assist. Prof.	anamika.dubey@wsu.edu	T/W
14.	Nanpeng Yu	UC-Riverside	Assoc. Prof.	nyu@ece.ucr.edu	O/W
15.	Junbo Zhao	Univ. Of Connecticut	Assist. Prof.	junbo@uconn.edu	O/E
16.	Xu Bolun	Columbia	Assist. Prof.	bx2177@columbia.edu	T/E
17.	Qifeng Li	Univ. of Center. Florida	Assist. Prof.	Qifeng.Li@ucf.edu	T/E
18.	Sijia Geng	John Hopkins	Assist. Prof.	sgeng@jhu.edu	T/E/SC6
19.	Amritanshu Pandey	Univ. of Vermont	Assist. Prof.	Amritanshu.Pandey@uvm.edu	T/E/SC5
20.	Jianhua Zhang	Clarkson	Assist. Prof.	jzhang@clarkson.edu	T/E/SC1
21.	Anuradha Annaswamy	MIT	Lab Director	aanna@mit.edu	O/E

22.	Sukumar Kamalasadan	UNCC	Distingh. Prof.	skamalas@uncc.edu	T/E
23.	Hao Zhu	UT-Austin	Assoc. Prof.	haozhu@utexas.edu	O/C
24	Hamed Mohsenian-Rad	UC-Riverside	Assoc. Prof.	hamed@ece.ucr.edu>	O/W
25.	S. Lotfifard	Wash. State Univ.	Assoc. Prof.	s.lotfifard@wsu.edu	O/W
26.	Ming Jin	Virginia Tech	Assist. Prof.	jinming@vt.edu	O/E/SC2
27.	Ramteen Sioshansi	Carnegie Mellon	Center Director	rsioshan@andrew.cmu.edu	T/E
28.	Paras Mandal	UT at El Paso	Assoc. Prof.	pmandal@utep.edu	T/W
29.	Mahnoosh Alizadeh	UC-Santa Barbara	Assoc. Prof.	alizadeh@ucsb.edu	O/W
30.	Anurag Srivastava	W. Virginia University	Professor	anurag.srivastava@mail.wvu.edu	O/E
31.	Vassilis Kekatos	Virginia Tech	Assoc. Prof.	kekatos@vt.edu	T/E
32.	Liang Du	Temple Univ.	Assist. Prof.	ldu@temple.edu	Local (L)/E/SC3
	US Speakers/Moderators (18)				
1.	M. Almassalkhi	Univ of VT	Assoc. Prof.	malmassa@uvm.edu	T/E/S
2.	D. Gross	U of W-Madison	Assist. Prof.	dominic.gross@wisc.edu	T/C/S
3.	I. Hiskens	U. of Michigan	Chaired Prof.	hiskens@umich.edu	T/E/M
4.	Z. Obradovic	Temple Univ.	Center Director	zoran.obradovic@temple.edu	L/E/S
5.	Q. Z. Sun	Univ. of Central FL	Assist. Prof.	QZ.sun@ucf.edu	T/E/S
6.	K. Tomsovic	Univ of Tennessee	Chaired Prof.	ktomsovi@utk.edu	T/E/M
7.	K. Baker	U of CO-Boulder	Assist. Prof.	Kyri.Baker@colorado.edu	T/C/S
8.	J. Mathieu	U of Michigan	Assoc. Prof.	jlmath@umich.edu	T/C/S
9.	R. O'Neill	ARPA-E, USA	Senior Advisor	richard.oneill@hq.doe.gov	T/E/M
10.	A. R. Ganguly	Northeastern	Center Director	auroop@gmail.com	T/E/S
11.	M. Kezunovic	Texas A&M Univ.	Regents Professor	m-kezunovic@tamu.edu	T/C/S
12.	S. M-Trento	EPRI	Lead, Strategic Issues	smullen@epri.com	T/E/M
13.	B. Kroposki	NREL	Center Director	Benjamin.Kroposki@nrel.gov	T/C/S
14.	Y. Dvorkin	John Hopkins	Assoc. Research Professor	ydvorki1@jhu.edu	T/E/S
15.	M. Lauby	NERC	Sr. VP and Chief Engr.	Mark.Lauby@nerc.net	T/E/M
16.	C. Smith	ESIG	Exec. Director	charlie@esig.energy	T/E/S
17.	S. Raju	U of Minnesota	Research. Assist. Prof.	rajux018@umn.edu	T/E/S
18.	E. Pistikopoulos	Texas A&M	Center Director	stratos@tamu.edu	T/C/M
	European Speakers/Moderators (18)				
1.	M. Polycarpou	U of Cyprus, Cyprus	Center Director	mpolycar@ucy.ac.cy	T/S

2.	R. Gupta	EPFL Switzerland	PostDoc	rahul.gupta@epfl.ch	O/S
3.	N. Hatziargyriou	NTUA, Greece, DERLab, Germany	Professor Emeritus	nhatziar@mail.ntua.gr	O/M
4.	B. Hammer	U of Bielefeld, Germany)	Professor	bhammer@techfak.uni-bielefeld.de	T/S
5.	P. Panciatici	RTE France	Sc. Advisor	patrick.panciatici@rte-france.com	O/S
6.	C. Dent	Univ. of Edinburgh & Alan Turing Institute	Professor	Chris.Dent@ed.ac.uk	T/M
7.	P. Koundouri	DTU, Denmark and Athens Univ, Greece	Professor	pkoundouri@aueb.gr	O/S
8.	P. Linares	Comillas, Spain	Professor	pedro.linares@iit.comillas.edu	O/S
9.	L. Nordstrom	KTH, Sweden	Professor	larsno@kth.se	T/M
10.	E. Spyrou	Imperial College, UK	Assistant Prof.	evangelia.spyrou@imperial.ac.uk	T/S
11.	D. Kroeger	TU Dortmund, Germany	Research Assistant	david.kroeger@tu-dortmund.de	T/S
12.	A. Ulbig	RWTH Aachen, Germany	Professor	a.ulbig@iaew.rwth-aachen.de	T/M
13.	J. P. Lopes	INESC, Portugal	Professor	jpl@fe.up.pt	T/S
14.	P. Taylor	Bristol, UK	Center Director	pvc-research@bristol.ac.uk	O/S
15.	N. Constantinescu	entso-e, Belgium	Director	Norela.Constantinescu@entsoe.eu	O/M
16.	M. Michael	U of Cyprus, Cyprus	Assoc. Prof.	michael.maria.1@ucy.ac.cy	O/S
17.	A. Chronis	NTUA, Greece	Research Assistant	achronis@power.ece.ntua.gr	O/S
18.	L. Olmos	Univ. Pontificia Comillas, Spain	Senior Researcher	olmos@comillas.edu	T/M
	European Invited Participants (6)				
1.	S. Chevalier	DTU, Denmark	PostDoc	schev@dtu.dk	O
2.	C. V. Martínez	Univ. Pontificia Comillas, Spain	Senior Assoc. Prof.	cvalor@icade.comillas.edu	O
3.	A-G. Exposito	Universidad de Sevilla-Spain	Professor	age@us.es	O
4.	P. Palensky	Professor	Delft Univ. of Tech. Netherlands	Peter.Palensky@tudelft.nl	O
5.	A. Papavasiliou	Assistant Professor	NTUA, Greece	papavasiliou@mail.ntua.gr	O
6.	György Dan	Professor	KTH, Sweden	gyuri@kth.se	T

Appendix C: Scribe notes from discussions on Topic 1

Panel Moderators:

I. Hiskens (U of Michigan, USA)
N. Hatziargyriou (NTUA, Greece, DERLab, Germany)

Panelists:

M. Almassalkhi (Univ. of VT, USA)
D. Gross (Univ. of Wisconsin-Madison, USA)
M. Polycarpou (U of Cyprus, Cyprus)
R. Gupta (EPEL Switzerland)

Scribes:

Baosen Zhang (Univ of Washington, USA)
Jianhua Zhang (Clarkson University, USA)

Presenters:

M. Almassalkhi: discussed the "**Roles of Utilities**"

- What role will utilities play 20 to 30 years from now? What do utilities look like now? New frameworks and control architectures are needed for the new power grid.

- We need new control architectures for aggregated DERs. Commit to market services (e.g., frequency regulation), and satisfy demands, we need to optimize resources across the grid by aggregating flexibility. There are 4 types of problems for aggregating DERs to support grid services. (1) Load management through simulation and data-driven studies. (2) What role does the utility play when we develop local control algorithms? We should know what we can control. Although the physical connection between DERs and the grid is clear enough, the exact data available to either is still unclear. We must avoid conflicts between who controls what and who knows what. We should know the interactions among DERs as that determines grid flexibility. This should be available to both the grid operator and the DER coordinator. (3) Increasing reliability challenges that could affect consumers, such as EVs or smart thermal loads. (4) Social impacts of implementing grid services.

- There are many ways to control DERs to deliver aggregated power services, such as frequency regulation. However, it is unclear what is measured versus estimated. How do we track the devices? Some are controlled through top-down methods, others through direct load control. The devices are directly communicating with the coordinator. It might be a top-down coordinator or a feedback coordinator. The open question is to estimate the external power resource available to the aggregator.
- What can a fleet of DERs do? How can uncertainty be taken into account? How about nonlinearities? How can performance be guaranteed? We need to incorporate decision-dependent uncertainty.
- Quantifying the flexibility that the grid can host remains an open question. What is the hosting capacity of the grid? How should DERs cooperate to achieve the stated flexibility of the grid?
- Utilities don't have the tools to implement sophisticated controls. Utilities may increase grid capacity (leading to rate increases) rather than network control. How can utilities move on from just hosting capacity analysis?

D. Gross discussed **"Grid as a Multiphysics System"**

The grid is becoming a system with the following features: (1) decentralized, sustainable, and resilience requirements, (2) heterogeneous technologies and control, (3) many devices, technologies, and timescales, (4) complex and poorly understood dynamics, and (5) microgrids with batteries.

- The first challenge concerns the interoperability and scalability of primary control time scales of emerging multiphysics systems based on power electronics. Specifically, interactions extend across vast spatial scales, and heterogeneous physics through rotating machines will persist. However, one of the main problems is that many technologies don't have standardized converter controls for renewable generation and are not fully interoperable. Furthermore, the physics and controls span multiple timescales from milliseconds to seconds, resulting in highly complex interactions. The second challenge concerns scalable analysis for multiphysics systems because current simulation tools and numerical methods do not scale well. Analytic stability conditions exist for microgrids with homogenous dynamics and 100% grid-forming controls. However, very limited results are available across timescales, and physical domains (e.g., power electronics, renewables, storage, AC/DC transmission) are available.

- Numerous ExamplesExamples of instability due to control interactions, instability across physical domains, network circuit dynamics, and harmonic instability have been demonstrated. End-to-end control and analysis frameworks and operating paradigms have been proposed for reliable and sustainable power systems. Specifically, the composition of homogenized device models, complex network models, and plants can enable (1) end-to-end models of power conversion, transmission, and generation, (2) uncovering of key features and interactions of constituent elements, (3) collaboration through control and power networks, and (4) communication and higher-level control and optimization.
- Ensuring the stability of emerging power grids will require analysis that uses first-principles analytic models for control and decision-making and captures interactions across physics, temporal, and spatial domains. This involves identifying technology-agnostic representations of physics and controls and employing real-time control principles that acknowledge complexity. Also, reducing spatiotemporal complexity through control and optimization is important.
- Moving towards self-organizing grids is challenging because the current operating paradigm is centralized. However, changing the current paradigm would be difficult to justify. Crucially, the current operation works fine most of the time, and changes to the current paradigm may only be justified when considering being justified when high-impact events are rare.

M. Polycarpou: Distributed Fault Diagnosis of Interconnected Cyber-physical Systems

Monitoring is very important for resilient power grids, which are moving toward more complex, large-scale, interconnected, interdependent, embedded SW/HW components and autonomous automation. An open question is how to design monitoring and control algorithms to address these technological trends. Power grids are examples of cyber-physical systems (CPS). Although complex, when we look at the system from the perspective of monitoring and control, they form a simple diagram with (1) System, (2) Monitoring, and (3) Control and feedback. The key question is monitoring and controlling for possible fault scenarios – sensor faults, controller, environmental faults, cyber-attacks, actuator faults, and system/process faults- the necessary diagnostic steps include event detection, event isolation, risk assessment, and mitigation. For interconnected CPS, faults could propagate, though a single agent may be employed to detect the fault source. In summary, some key challenges include partitioning into subsystems, fault/attack propagation, handling heterogeneous data, control to enhance monitoring, performance versus resilience, distributed fault diagnosis of evolving systems, and achieving lifelong monitoring.

R. Gupta: Controlling DERs in Active Distribution Grids Under Model Uncertainty

Both USA and Europe are experiencing considerable DER growth, which is highlighting the impact of uncertainty. The main challenges occur in operating distribution grids with a high share of PV and wind generation in both transmission and distribution grids. Grid-aware flexibility used in distribution grids can support both transmission and distribution grids. Measurement and monitoring systems are required for DER control. The impact of grid model uncertainties on grid-aware control can be managed through microgrid control strategies. Control formulations must include an uncertainty model; however, the estimation of parameters is a challenging problem. Online learning methods that use heterogenous data offer technologies for better-managing uncertainties, but numerous open research challenges remain.

Discussion:

Q1: Does optimal deployment of large numbers of grid-forming IBRs need to consider device-level converter dynamics?

A1: The locations of grid-forming IBRs and their control strategies certainly affect their ideal operating conditions for analysis methods available today.

Q2: System-wide standards are needed. Interconnection standards are required. However, over-prescriptive standards should be avoided.

Q3: The concept of power systems is changing dramatically, driven by social and environmental goals and policy requirements. As we move towards wide deployment of DERs, many questions arise regarding control architectures, operation strategies, and distributed and deployable capability. How do we meet this objective of deploying DERS to maximize their capability?

A3: Some top-level optimization is needed, but some operations should remain distributed to achieve robustness and meet privacy concerns.

Q4: What tools are needed to simulate the control and coordination of active distribution grids?

A4: At a high level, we should study problems like optimal power flow for distribution grids. This should include all relevant DERs, for example, EV charging infrastructure, and carefully incorporate network constraints. There is also a growing need to study dynamic interactions between DERs across a wide range of time constants constraints.

Grid Resilience. New events like wildfire and smoke require new thinking about resilience. Resilience metrics are not clear. Social aspects and rare events make it hard to define metrics and risks. The tradeoff between performance and resilience. Resilience from a dynamical point of view. It's not a step response, but we don't have a formal way of handling it. Not a formal definition of resilience.

Appendix D: Scribe notes from discussions on Topic #2

Topic 2: ML/AI data modeling method and computational advances for flexible grids

Panel Moderators:
K. Tomsovic (U of Tennessee, USA)
C. Dent (Univ. of Edinburgh, and Alan Turing Institute, UK)

Panelists:
Z. Obradovic (Temple, USA)
Q. Z. Sun (Univ. of Central Florida, USA)
B. Hammer (U of Bielefeld, Germany)
P. Panciatici (RTE-France)

Scribes:
Yan Li (USA)
Ming Jin (USA)

Presenters:

Zoran Obradovic: ML in Temporal Networks

The presenter first discussed common assumptions made in ML, including

- Distribution remains consistent: The model is trained on one dataset and applied to another with the same distribution.
- Functions are smooth almost everywhere: This strong assumption assumes that the function is smooth in most situations.
- High signal-to-noise ratio: The quality of the data is crucial for accurate results.
- Quality labels: In supervised learning, the assumption is that labels are accurate and high-quality.

In reality, complex systems have complicated relationships, and many of these assumptions may be violated. Data is anonymized. The signal is inconsistent. Labels are imprecise. Observations are scarce. Some important challenges to consider inconsistent labels, small effect sizes, and noisy observations. When faced with practical challenges, it's essential to adapt ML methods to address these issues.

Then, the presenter shared a recent project using PMU data, where the data was massive - reaching petabytes in size. This required the development of new protocols for transferring data from various sources. The sheer size of the data presented significant challenges for both data management and analytics. Due to proprietary reasons, the data came from multiple utilities, and spatial information was not provided. This limited our ability to use potentially valuable spatial data. The missing rate was also extremely high, and the data quality varied significantly. The status of PMUs (phasor measurement units) could not be relied upon as quality indicators for all data points. These challenges highlight the complexities involved in working with large-scale, real-world data.

Another challenge, as highlighted by the presenter, is shifting from reactive to proactive approaches in addressing issues. Typically, when an event occurs, such as a system failure, we want to identify the cause and quickly fix it. However, a proactive approach, which involves predicting potential disruptions, would be more efficient.

Specifically, the presenter discussed a project on predicting disruptive events in power networks. By predicting the likelihood of certain disruptive events happening at specific locations and times, one can take preventive measures to reduce damages or even eliminate the issue. One example of this is predicting weather-related outages. In the Pacific Northwest region, the probability of outages can be predicted within a three-hour window. On the left side of the example, most areas were marked green or gray, indicating low probabilities of outages during an approaching storm. On the right side, several areas were circled in blue, highlighting the high probability of outages in those locations. Ultimately, our predictions successfully identified all significant outage events. While progress has been made in predictive analytics, more work is needed to further develop and refine these techniques.

Another aspect discussed by the presenter is understanding the precursors or causes of specific events. Knowing why something happened is crucial for improving future performance and making better decisions. However, from an ML perspective, this problem can be difficult because labeled data often doesn't provide much information about the causes of the events.

To tackle this issue, the problem was formulated by examining specific timeframes or "bags" before the event and determining which explanatory variables to focus on. This precursor analysis can help us identify the influential factors that led to the event. However, in that study, limitations are faced due to the lack of spatial information about the locations of the events. Another project is currently undergoing where there is access to spatial data, which should lead to more accurate and informative results.

One challenge encountered is that when the weather is extreme, we often have more missing data than usual. This also affects weather stations in locations like Alaska, where data is frequently absent when we need it most. A possible solution to enhance ML quality in these situations is to use social media. People nowadays post a wide variety of content on social media, including information about their local weather conditions. We can extract this information from platforms like Twitter and Reddit to use as additional, albeit low-quality, data. This approach requires natural language processing and other techniques, but it has shown promise in improving the quality of ML models. By incorporating weather data and social media insights, we can create more accurate and reliable models that consider the real-time conditions experienced by people in various locations.

In conclusion, some people seem to believe ML is a cure-all for every problem, much like how everything is supposedly better with bacon. However, ML is not perfect. Some of the issues mentioned include anonymized data, scarce information, and low precision. Despite these challenges, there are ways to work around them and still extract valuable insights from low-quality data that may violate various assumptions.

One important aspect to remember is that we need better standards for collecting data, especially when it comes to data from multiple utilities. This will be more helpful than simply relying on ML alone. Furthermore, it's essential to recognize that ML is just one tool in the toolbox. We should also leverage the wealth of knowledge available from other disciplines, such as physics, to help us make sense of complex data. We can create more effective and accurate models by integrating these different areas of expertise.

Qun Zhou Sun: How Can Data Help Build a Flexible Grid? ML/AI data modeling method and computational advances for flexible grids in the context of smart buildings

To the presenter, buildings are an umbrella term for all sorts of demand-side distributed energy resources, such as HVAC systems, water heaters, solar panels, and batteries. These resources are somewhat controllable but are small compared to large power plants. She calls them distributed resources, and their presence already creates challenges for energy and market management systems. In market management systems, every resource, such as gas turbines, steam turbines, and wind farms, must be modeled first. However, modeling buildings is extremely challenging due to their unique characteristics and diverse components.

Indeed, there are significant efforts required to accurately model building energy consumption. There are various approaches, such as physics-based modeling and data-driven modeling. These methods help us understand the intricacies of HVAC systems, which can be quite complex, similar to power systems with transformers and heat exchangers.

HVAC systems need to manage not only electrons but also air, water, refrigerants, pressure, and flow, which makes them quite complex. If we want to accurately model a building's energy consumption, we can use tools like EnergyPlus or Modelica. Sometimes, these models are called digital twins. It can take months to build these models, and after that, there's still a need for calibration, verification, and validation before they can be used effectively.

However, if the ultimate goal is to use these models for control purposes, it's essential to simplify them into control-oriented models. This process requires much effort and resources but is crucial for developing efficient and flexible grid management systems.

The presenter first discusses uncertainty in building modeling. Some data-driven models use large amounts of high-dimensional spatial-temporal data collected from buildings. These models can be built using regression, time series analysis, neural networks, decision trees, and other methods. Generally, data-driven models are easier to build than physics-based ones but can be challenging to generalize.

Hybrid models, which combine domain knowledge and data, have been used to balance the trade-off between modeling efforts and accuracy. These models embed domain-specific knowledge, such as heat transfer equations. Although their accuracy can be high in some cases, it's important to note that the accuracy tends to decrease as the spatial resolution becomes finer.

Comparing building energy modeling to load forecasting – the accuracy may be lower, but this is partly due to the complexity of modeling human behaviors and fluid dynamics. It may be unrealistic to expect building energy modeling to achieve the same accuracy level as power system models. Instead, it's essential to acknowledge and quantify uncertainties using data. Focusing on tools that provide forecast confidence intervals can be more beneficial than seeking higher accuracy. We can make more informed decisions and better manage flexible grids by embracing uncertainties and optimizing control methods.

Then, she presents flexibility quantification. One potential use of data is quantifying the flexibility of building energy systems. Flexibility is loosely defined as the ability to adjust power usage within a specified period without compromising occupant comfort. Factors such as controls, building operating conditions, and set points can impact flexibility. Changing the set point can reduce energy consumption, but the flexibility will vary depending on the building's operating and non-operating points.

Flexibility quantification must be dynamic and real-time, affected by weather, human activity, equipment, controls, and grid signals. Collecting and organizing building data allows us to analyze various factors as features and examine response variables like energy consumption and room temperature. For example, using 2018 UCF campus building data to represent a typical meteorological year, a building performance database was created that includes grid-independent and grid-interactive buildings. This database can be expanded into a flexibility quantification database to explore the relationship between resource operating conditions and energy flexibility.

By using supervised ML methods to train the data, a lookup table can be created that grid operators can use to better manage flexible energy resources. It's essential to remember that quantification of flexibility should also consider associated uncertainty estimation.

This leads to the topic of data-driven decision-making. Ultimately, these flexibility models serve as inputs for decision-making tools. To participate in the market, it's necessary to aggregate the flexibility of many buildings, develop aggregated data, and create bidding strategies based on this information. When market signals are received, they must be disaggregated back to individual resources while ensuring that occupant comfort is not negatively impacted.

This process falls within the optimization domain under uncertainty, an area that has been researched extensively, particularly in solar and wind integration. However, it's important to remember that buildings have higher uncertainties, and efforts should be made to reduce these uncertainties and increase the flexibility of individual resources.

By developing incentive programs, we can encourage the adoption of measures that decrease uncertainties and increase the flexibility of individual resources, ultimately leading to more efficient energy management and market participation.

In summary, data can help in the following ways:

- Quantify building modeling uncertainties using Bayesian inference. Combining this with domain knowledge may yield more robust probabilistic results, enabling confidence interval analysis.
- Use data to quantify building flexibility as a function of various variables, allowing for better understanding and management of resources.
- Develop data-driven market participation strategies by aggregating uncertainties and flexibility, leading to more efficient participation in energy markets.
- Enhance system controls by aggregating them down to individual resources, allowing for more precise management and control of energy resources.

Barbara Hammer: ML Technologies in Critical Infrastructures – Opportunities and Challenges

The presenter starts discussing opportunities and challenges. She believes the challenges and opportunities in the electric grid domain mirror those emerging in ML, making it an ideal testing ground for new developments.

In smart grids, there are numerous agents, such as energy producers, consumers, devices, and objects with dual uses, like storage and consumption. Challenges include short-term optimization control, long-term planning, decision support, and enhancing security against attacks or major failures. These challenges can translate into classical ML tasks such as demand prediction, state estimation, policy learning, and unsupervised data analysis. These ML tasks can help identify crucial features or measurements that significantly impact the entire system, leading to better management and optimization of the smart grid.

One issue that complicates learning within these systems is that agents might change, and they are not uniform. The network resembles a graph where a consumer or other agent might enter or leave, and some power system parts may have different numbers of agents to exchange information with. This complexity aligns with a recent topic in ML – geometric deep learning or learning with structured data.

Geometric deep learning allows directly integrating graph structures, with possibly varying topology, into ML tools. This approach can accommodate spatial information with various nodes and even dynamic graphs where the number of nodes and connections change, much like in a power grid.

In one example, a graph neural network was used for a critical infrastructure network. While it is not an electrical grid but a water distribution system, the problems are quite similar. In this case, a graph neural network has been used to address the problem of virtual sensors related to observability issues. Observing a particular quantity only at specific points in the network might be possible.

In this example, only 5% of the network is covered with sensors that can observe pressure (in an electric grid, this would involve different sensors and values). A specialized graph neural network can predict the values from the observable sensors for control points that cannot be directly observed. This comes with challenges, as there are different types of graph neural networks, such as convolutional neural networks and message-passing ones. The topology of this network calls for message-passing, as it has unique features like very long lines with only a few nodes on them.

In one of the examples, the predicted value aligns closely with the true value, unlike other classical models like prediction based on Fourier transformation.

Another issue in the electric grid and ML is the presence of temporal data. Over long periods, data may change due to various factors, such as seasonal consumption differences or the introduction of new devices. This problem is typically present in what is called incremental learning, where you have a stream of data with critical properties that might be non-stationary. This violates one of the most important assumptions in classical ML, which is that data should be identically distributed.

This leads to the stability-plasticity dilemma, where one must decide which information from the trained model is still valid and which new information needs to be integrated. Incremental learning models are designed to address this issue by adapting to changes in the underlying data over time.

The next example, combined with an adaptive process, can determine which data and model components are still relevant, allowing it to learn from streaming data even when the underlying distribution changes. This ensures that the model remains up-to-date.

One benchmark dataset is "electricity," which predicts price evolution over time. Such models can also be enhanced with online interpretability, as seen in the lower right of the example. As the model develops and maintains good predictions, its internal structure might change. This can be observed in the changing relevance of specific features during the model's development. By incorporating explainability elements into the model, we can better understand its decision-making process over time.

In the next slide, she discussed the challenges arising from the involvement of people in various roles, such as customers, decision-makers, domain experts, and even potential intruders. People may inadvertently disrupt the system by producing noisy data or affecting its stability. ML systems must offer interaction possibilities with humans so that they can integrate their expert knowledge and trust the system.

ML technology must consider human factors in critical infrastructure, as outlined in the European Ethics Guidelines for Trustworthy AI. Trustworthy AI must preserve human agency and ensure robustness, transparency, diversity, privacy, and other essential aspects.

To delve deeper into transparency, which can be achieved through explainability in modern methods. Instead of relying solely on black-box deep learning methods, we should enhance them with explainability mechanisms that allow individuals to challenge the model and understand the underlying functions that drive its results.

In the next slide, she presents an example of a black-box explanation technique using counterfactual explanations. Counterfactual explanations, originating from philosophy, challenge a model by asking what should be different in order to produce a different output. For example, when observing a sensor fault in a system, we can ask what should be different for the sensor not to register the fault.

We use this principle of counterfactual explanations alongside ML models to explain why a sensor fault is detected through residual analysis. This can help us determine which of the overall explanations caused the sensor fault. As seen in the upper right corner, we can phrase this as a constraint optimization problem, which can be solved using black-box optimization methods or, in the case of simple models, even analytically or with polynomial regression.

In the example, the output profile tells us which measurement is most responsible for detecting the failure. Errors may propagate, so knowing which sensor is at fault can be difficult. However, this technique offers an opportunity to identify the most critical fault according to the system, which can help detect the fault and pinpoint where it occurred.

So far, the presenter has highlighted three challenges: dealing with spatial data using graph neural networks, addressing temporal developments through incremental learning, and providing explanations for humans with explainability techniques. However, further challenges arise due to ML, such as:

- ML being brittle itself: Adversarial attacks or data poisoning can lead to the need for robust ML methods.
- Biases and peculiarities in the data: These can result in unfairness or biases in the models, which must be addressed to ensure equitable outcomes.
- Privacy issues: Differentially private learning models may be necessary to protect sensitive information.

- Energy consumption: Deep learning networks, in particular, can be power-hungry, potentially increasing energy demand and posing additional challenges to the system.

Patrick Panciatici: Decision-making problems in large power systems: physics informed ML

The presenter discusses energy transition and the coordination of large populations of agents/devices. As the complexity increases, we need to coordinate a growing number of adjacent devices with partial autonomy. This is a significant shift from when we dealt with larger, less active stochastic agents. For example, a big power plant in the past might transform one gigawatt, whereas a wind farm in France today produces only 150 megawatts. We must send 20 control signals to a wind farm to have the same impact on the system.

Additionally, we now have millions of smaller devices, such as rooftop PV panels, which can be challenging to manage. As a result, we must develop a new approach that accommodates greater dispersion, innovation, and more active consumers or prosumers in the system. This change can create localized congestion and integration challenges, as the location matters for balancing the grid and managing power links or cables with limited capacity.

To address these issues, he believes that more local control is needed for efficient system management. As we incorporate renewable energy sources into the system, we must be mindful not to overbuild. For instance, we use 70% of the installed capacity in France to integrate. If there is excessive power in an area, we may need to cut power from wind farms or PV panels. To achieve this efficiently, we must use all possible local actions, such as grid configuration or collaboration with neighboring countries like Germany.

However, this level of complexity requires automatic controllers to manage the multitude of small objects and complex limits. By developing and implementing these new strategies, we can better adapt to the changing energy distribution and management landscape.

The presenter and collaborators have developed a new architecture that, while not overly sophisticated, expands upon past methods. Previously, congestion management only involved an optimization layer in preventive control and a protection layer, with nothing in between. Now, we aim to introduce a new control layer that implements automatic control for congestion management. Using a car analogy, the optimization layer is similar to a navigation assistant like Waze, defining optimal trajectories. The control layer resembles a self-driving car, and the protection layer includes airbags and automatic emergency brakes to avoid catastrophic impacts. They have designed this new controller, and the next challenge is to effectively integrate the control layer with the optimization layer.

We must consider various factors when defining optimal trajectories, such as consumer uncertainties and the presence of control layers that handle certain issues. This creates a complex optimization problem that requires a combination of classical optimization and physical information.

In classical optimization, we have always made approximations or used screening due to the complexity of the problems. However, these methods may not be robust or fast enough for near real-time applications. Given the increasing complexity, We think replacing heuristics with ML is a good idea.

ML, while not a magical solution, combined with our understanding of the system and underlying physical laws, can help solve complex problems. By leveraging this knowledge, we can achieve better generalization capabilities, more trust in the methods, and more efficient training, ultimately leading to improved outcomes.

In power grids, we work with graphs representing the system, consisting of nodes and branches, inputs, and outputs. Voltage phase and magnitude are defined at these nodes, and these points have injections (generation, consumption). Links between nodes can be asymmetrical, for example, due to a phase shift of a transformer.

Integrating this information into ML techniques can be challenging, as fully connected neural networks may struggle to represent these structures. Traditional ML techniques usually require flattening data into vectors or images unsuitable for graphs. To address this issue, we developed the idea of graphical networks.

The concept of graph networks allows us to mimic the power grid structure within ML techniques. These networks enable us to pass information through the graph to estimate values or find optimal decisions. In this approach, all information flows through neural networks, with the graph structure serving as input, incorporating physical information.

We can run these networks offline, using simulations or archived real-time data, or apply them to minimize violations of physical laws. This method allows for adaptability to changes in the graph, such as adding or removing edges or nodes, while maintaining robustness and computational efficiency.

In conclusion, the increasing complexity of our systems demands the coordination of a large population of agents or devices with partial autonomy. We are dealing with cyber-physical systems of systems, making it quite different from traditional approaches. Combining ML and classical optimization control methods may be necessary to find implementable solutions while maintaining robustness and reliability through underlying physics. This is why physics-informed learning is a promising approach for critical systems.

However, ML for decision-making is not fully mature yet. While there are proofs of concept and impressive results in smaller examples, more extensive demonstrations still need to be conducted. It's crucial to remember that network topology variability is inherent in these systems, as they change over time due to planned outages or faults. Solutions must account for this variability.

Discussion

- **Topic:** Challenges faced by deep learning and ML techniques, particularly with the surge of interest in AI-driven autonomous vehicles. **Summary:** The major challenges highlighted include the difficulty of embedding physical knowledge into AI models, improving algorithms to incorporate physical equations, scaling up models from simple to complex without compromising computational efficiency, and balancing between iterative processes or simplifying models for integration into optimization. Furthermore, the need for a more robust approach to handle high-dimensional and imbalanced data situations, the incorporation of domain-specific knowledge and real-world constraints, and the development of novel techniques to handle complexity were also underlined. There was also an emphasis on the potential benefits of integrating ML with other methods to improve user outcomes and customized solutions. In addition, the growth of generative approaches in ML that could aid in learning from unlabeled data was noted.
- **Topic:** The possibility of non-physical connectivity within power grids, particularly in inference graphs where nodes that are not physically linked might still influence each other. **Summary:** The speaker affirmed that such instances could exist and could be facilitated by techniques such as inference graphs to expedite computations. Although these methods do not create a new form of connectivity, they can enhance computational speed, which is the primary objective. While the influence over remote nodes through physical connections may be limited, non-physical links in inference graphs could expedite computations and have an indirect impact.
- **Topic:** Explainability of ML and different perspectives towards data handling in the context of power systems. **Summary:** Challenges in deploying ML solutions, particularly in the medical field, were discussed, highlighting the need for certainty and the ability to provide clear explanations for predictions and recommendations. The speaker stressed the necessity for communication to be tailored to the audience to ensure their understanding, suggesting that additional visual communication tools could bridge the gap between ML and practitioners. Ultimately, the speaker emphasized the importance of focusing on explainable ML, providing understandable explanations for its applications, as a critical factor for success.

- **Topic:** The discussion pivoted around contrasting perspectives on data handling and power system architecture, considering the roles of these views in evolving power systems. **Summary:** The debate between centralized optimization, known for its reliability, and distributed optimization, focused on individual demands and resiliency, was acknowledged. It was suggested that both could coexist due to varying interests and stakeholder priorities. The ultimate choice would depend on the trade-off between investment costs, communication expenses, and the reliability each approach provides. A difference in approaches between statisticians and computer scientists was noted, with statisticians focusing on problem accuracy and global optimization, while computer scientists emphasize computational feasibility through approximation and decomposition. The practical application calls for an incremental process balancing quality and time constraints and a flexible switch between the two perspectives to derive feasible solutions.

- **Topic:** The decomposition approach for solving complex problems, emphasizing the need to balance quality, accuracy, and computational feasibility, often achieved incrementally while considering time constraints and practicality. **Summary:** The speaker stressed the importance of using accessible data sources effectively, which can be freely available or provided to academic institutions. The impact of weather variability on power systems was highlighted, noting the challenges centralized systems might face correlating weather changes with system behavior due to the rapidly fluctuating conditions over short distances. The speaker advocated focusing on localized conditions, optimizing the system by understanding and addressing local situations to solve the broader problem.

- **Topic:** The integration of uncertainty, particularly in communication, within the modeling process and the selection of optimization techniques for specific applications such as building systems. **Summary:** It was highlighted that choosing an optimization method depends on several factors, including performance, computational costs, and efficiency. However, a gap was noted between research and the practical application of these techniques in utilities, underscoring the need for further research to evaluate different methods. Incorporating uncertainty can be challenging, and the choice of approach depends on the nature of the uncertainty and the specific application. Integrating uncertainty into decision-making processes for other applications may involve structured learning and multiplex graph methods, among others. The optimal approach would be contingent on the specific application and the nature of the uncertainty.

- **Topic:** Using data sets, ML for optimization, and physics-aware AI in system optimization. **Summary:** The speaker highlighted the importance of high-quality data sets for effective ML, indicating the variance in their current availability depending on the application. Simulation-based methods could supplement existing data by generating synthetic data sets. When leveraging ML for optimization, critical questions include defining the objective function, recognizing the constraints, and understanding the available data to train the model. The speaker advocated for physics-aware or physics-inspired AI in system optimization for more robust and reliable outcomes rather than simply substituting traditional optimization methods with AI or ML approaches.

Below are detailed questions and answers.

Question: with renewed interest in AI, particularly driven by autonomous vehicles, I wonder what challenges will be difficult to tackle for deep learning and ML techniques.

Speaker 1:

- AI research has had ups and downs, with neural networks being exciting but not always delivering on promises. Problems are not as easy as marketing makes them seem, and the community needs to avoid overpromising and refocus.

- Academics should guide students towards more important, difficult problems rather than making little incremental progress.

- Real-life problems require hard work, understanding limitations, and not just applying ML tools to data.
- High-dimensional situations and imbalanced data present challenges that need to be addressed for progress to be made.

Speaker 2: The challenges include:

- Embedding physical knowledge into models:
    - Integrating domain-specific knowledge and real-world constraints into ML models.
    - Ensuring accurate representations of the underlying physical processes to improve model performance and generalization.
    - Combining data-driven approaches with expert knowledge to create more robust and accurate models.
- Improving algorithms to incorporate physical equations:
    - Adapting ML algorithms to work with physical equations rather than just data.
    - Developing novel algorithms and techniques to handle the added complexity of physical equations in the modeling process.
    - Ensuring algorithms can learn effectively from both data and physical constraints.
- Scaling up models from simple to complex, affecting training and inference time:
    - Developing efficient methods for training and inference in large-scale models with many nodes and connections.
    - Balancing model complexity with computational resources and time constraints.
    - Addressing challenges related to overfitting, underfitting, and model generalization as models scale up.
- Difficulty in using data-driven models for optimization:
    - Many optimization techniques are designed for simpler models and struggle with complex, data-driven models.
    - Developing optimization methods that can handle the complexity and nonlinearity of data-driven models.
    - Ensuring that optimization techniques can effectively leverage the information contained within complex models to find optimal solutions.
- Balancing between iterative processes (modeling and optimizing) or simplifying models for integration into optimization:
    - Deciding whether to use an iterative process, where modeling and optimization are performed separately or to integrate the model directly into the optimization process by simplifying it.
    - Determining the trade-offs between model simplicity and accuracy when integrating models into optimization.
    - Investigating techniques for model simplification that maintain the essential characteristics of the original model while making it more amenable to optimization.

Speaker 3: As for ML, generative approaches are developing rapidly compared to discriminative ones. This could make it easier to learn from existing data, especially when labels are unavailable. This is certainly an advantage when dealing with imbalanced data and similar challenges.

Speaker 4:

- It's crucial to understand more and explore ways to integrate ML with other techniques
- Combining ML and optimization is advocated: Using ML before optimization can help reduce complexity and improve heuristics, resulting in better user customization. After optimization, ML can refine approximations and find more feasible solutions. We can also include optimization as part of the ML pipeline.
- Mixing ML with other methods aims to achieve more advanced heuristics and improved outcomes.

Question: Are there instances of non-physical connectivity within the power grid, such as an inference graph, where nodes A and B may not be physically connected but can still influence each other?

Speaker:

- Non-physical connectivity instances may exist in power grids, such as in inference graphs where nodes A and B are not physically connected but can still influence each other.
- Message-passing techniques in neural networks may be inefficient, so alternative methods are needed to speed up message-passing. Inference graphs and other graph-based techniques are used to improve computation speed.
- The main goal is to enhance computation speed rather than define a new form of connectivity.
- Local connections exist in the power grid, and while remote nodes cannot be directly influenced, non-physical connections in inference graphs could still have an impact by accelerating computations.

On the topic of the explainability of ML

Speaker 1:

- Understanding customers is crucial, as a gap between ML development and utility applications may exist.
- Challenges arise in deploying solutions in practice, as evidenced in the medical field, where accuracy and certainty are required. Clinicians and practitioners ask questions about certainty, requiring explanations for predictions and treatment recommendations.
- To ensure understanding, communication must be tailored to the audience, whether in medical or utility applications. Developing additional tools to visually communicate reasoning can bridge the gap between ML and practitioners. Focus on explainable ML, providing appropriate explanations for utility applications, is essential for success.

Moderator: Audience comments have touched on two different perspectives:

- One perspective suggests that we don't need to rely on large data sets and extensive quantization as the power system becomes more complex.
- The other perspective promotes a more decentralized architecture that focuses on computation and data exchange.

The panelists and audience members are invited to share their thoughts on the relative roles of these approaches as we move forward into the future with very different power systems.

Speaker 1:

- Centralized optimization vs. distributed optimization: An ongoing debate in bulk power systems and distributed energy resources.
- Coexistence for a long time: Both approaches may exist together due to the different interests and priorities of stakeholders.
- Reliability: Centralized power systems provide reliability, while distributed energy resources focus on individual demands and resiliency.
- Control preferences: In terms of actual control, centralization might be preferable.
- Cost considerations: The ultimate decision depends on the trade-off between investment costs, communication expenses, and the level of reliability that each approach can bring to the system.
- Stakeholder influence: Different stakeholders will continue to push for their preferred approach, shaping the future of power systems.

Speaker 2:

- Conflict of perspectives: statisticians focus on assumptions and global optimization, while computer scientists prioritize approximation and decomposition
- Different approaches: statisticians insist on having the "right" problem, whereas computer scientists focus on computational feasibility
- Incremental process in practice: balancing quality and time constraints
- Striking a balance: switching between the perspectives of a statistician and a computer scientist to find feasible solutions

On decomposition approach for solving complex problems:

Speaker 1:

- Balancing quality and accuracy with computational feasibility
    - The approach is often incremental, finding the right balance
    - Consider the time needed for better quality versus practicality
- Using accessible data sources
    - Some sources are free or provided to the universities
    - Important to use available data effectively
- Weather variability and its impact on power systems
    - Weather changes over short distances and time
    - Centralized power systems may struggle to correlate weather with system behavior
- Focusing on localized conditions
    - Look at specific feeders and their conditions
    - Optimize by understanding local situations to address the overall problem

Question: How can we effectively incorporate uncertainty in the modeling process, especially in communication? Given the various decision-making and optimization methods available, such as robust optimization, stochastic optimization with transfer constraints, and Bayesian techniques, which approach should we choose for specific applications like building systems? Moreover, how can we integrate these models with uncertainty into the decision-making and optimization processes for other applications?

Speaker 1: Various optimization techniques have been studied and are available for consideration. The choice of a specific technique depends on factors such as actual performance, computational costs, and efficiency. However, as far as I know, utilities may not currently use these techniques. A significant gap exists between research and practical applications in this area. It is important to conduct further research to evaluate the performance, efficiency, computational costs, and implementation costs of different techniques and any associated overheads.

Speaker 2: Incorporating uncertainty in the modeling process, especially in communication, can be challenging. Various decision-making and optimization methods are available, such as robust optimization, stochastic optimization with transfer constraints, and Bayesian techniques, that can be used for specific applications like building systems. However, the choice of approach depends on the nature of the uncertainty and the specific application.

In addition, it is essential to integrate models with uncertainty into the decision-making and optimization processes for other applications. One approach is structured learning, where a graph is observed over time, and uncertainty in each node can vary over space and time. A multiplex graph with multiple layers of information and dependencies in different locations can also be used. Such methods can handle multiple and complex graphs, and benefits have been observed. However, there are other ways to handle uncertainty, and the choice of approach depends on the specific application and the nature of the uncertainty.

Question: Could you elaborate on the types of data sets necessary for effective ML, the current availability of data sets, and whether simulation-based methods can be used as an alternative? Also, what are the essential questions to consider when using ML for optimization, and what are your thoughts on using physics-aware or physics-inspired AI in optimizing systems?

Speaker: In order to effectively use ML, the availability of high-quality data sets is essential. The current availability of data sets varies widely depending on the application, but many publicly available data sets can be used for ML. In some cases, simulation-based methods can be used to generate synthetic data sets to supplement the available data.

When using ML for optimization, there are three essential questions to consider: (1) What is the objective function? (2) What are the constraints? (3) What data is available to train the ML model? These questions are critical to ensure the ML model can optimize the system effectively.

In optimizing systems, using physics-aware or physics-inspired AI can be a better approach than simply replacing existing optimization methods with ML or AI approaches. By incorporating physical laws and principles into the optimization process, the resulting system can be more robust and reliable.

Appendix E: Scribe notes from discussions on Topic 3

Topic 3: Social, behavioral, and economic science synergy with the electric grid transformation

Panel Moderators:

Richard O'Neill (US)

Lars Nordstrom (Sweden)

Panelists:

Kyri Baker (US)

Johanna Mathieu (US)

Phoebe Koundouri (Greece)

Pedro Linares (Spain)

Scribes:

Timothy M. Hansen (US)

Liang Du (US)

Presenters:

Kyri Baker of the University of Colorado Boulder presented on how to design *demand response* (DR) using the differences in the community.

- DR depends on the type of customer:
    - Average customer (education) may be hard to do (may not have time to manually make decisions)
    - Studies show that low-income customers have deeper challenges in adopting demand response than high-income customers. Lower income customers are more available in the middle of the day – may increase costs for Time-of-Use pricing, however they may be more available to participate in DR
    - High income consumers may have the technology to participate in real-time, but are not price responsive (lower price elasticity)
- The grid is changing, there is a projected 900% increase in electricity consumption in the coming years.
    - This will increase the energy burden on lower income customers.
    - This also leads to the need for more real-time DR, and not just from high income users
- Research question is "can we and how do we design demand response to harness the diversity of communities to help the grid?"

Johanna Mathieu of the University of Michigan discussed the need to include *energy justice* in the power systems research agenda.

- Energy justice includes making energy more affordable and accessible for different (and marginalized) communities, especially marginalized communities
    - Borrows the definition from the White House Justice40 initiative
    - There is hidden energy poverty (customers making themselves uncomfortable to reduce energy burden)

- Most existing work has been on the social science end
    - Not using the same keywords as social science research are using, so hard to find/link research across domains
    - It is important to push cross-disciplinary research initiatives
- The research focus should systematically incorporate energy justice into power systems research, e.g., expansion planning and equitable incentives.

Phoebe Koundouri of the University of Athens described sustainability, climate neutrality, and resilience through *Sustainable Development Goals* (SDGs).

- Affordable and clean energy is challenging and major challenges remain
- Sustainability goal 13 related to the climate is very linked with the electric grid
- Studies have shown that combination of different models and designs have the potential to ensure energy equity.
    - Co-design with national and subnational groups to lead to climate resilience and neutrality
    - To create programs that can actually be implemented, you need a multi-disciplinary group
- Transition to environmental neutrality needs more qualitative studies.
    - Majority of governments failed to implement sufficiently ambitious green recovery plan
- 13 million jobs in clean energy sectors created, however emerging and developing economies are not close to the climate goals

Pedro Linares of Universidad Pontificia Comillas highlighted the *role of electric demand* in the electric grid transition.

- Need for a holistic overview of generation, integration, and resources in a more distributed, uncertain manner
    - Will have less flexible generation, but will be much more integrated (water, hydrogen, transportation), distributed, intelligent, and uncertain
- It is necessary to emphasize that demand profiles need to be better understood.
    - Modeling the rationality, preference, and flexibility of end users would incorporate another layer of social and behavioral science into the transition of greener energy.

Summary of the moderated discussion:

- Question/comment: Demand response is important, but to get effective consumer it is important to have devices like energy management systems that are cheap to help manage consumers building energy. We expect people to be responsive with the availability of solutions like this to provide flexibility.

  Discussion:

    - **Energy literacy:** most people do not know what their largest energy users are, so how do they know which to target to save money?
        - Smart thermostats can be provided from utilities but many people are renting so there is no incentive or ability to install them. Need the landlords to make these changes.

- Study by Brattle Group where they specifically sectioned out low/high income and found low income responded to DR just as well as the high income.
  - Demand is very heterogeneous. Segments of people are very responsive, others not so responsive.
  - Targeted policies will be important to extract all of the grid flexibility.
- Important for people to understand where the directed changes are coming from: why do we need to change energy sources, change and learn to use new appliances, and respond to all this provided data?
  - Many people do not connect electricity use with climate change; climate change with extreme weather events; and then the need to mitigate climate change through change in electricity behavior (and sources
  - There is a need to highlight the value proposition through awareness combined with incentives (not just price, but can be other societal values); if not, we will not change behavior because a behavior changes with incentives.
- Summary: End users do not really understand their energy profiles and lack proper incentives and awareness. Behaviors could change based on incentives, but again users need to fully understand what is clean energy and the energy transition.

- <u>Question/comment:</u> How do we bridge the knowledge gap; the user experience is with the thermostat/energy management system that an average person probably does not care about; what do people care about with respect to their power grid interactions?

  <u>**Discussion:**</u>

  - They <u>**do care**</u> about climate change, but much more concerned in the short-term with rates, reliability, and the impact of extreme weather, such as flooding.
    - Customers in the Midwest have major issues with appliances in basements that were flooded.
    - From this, they are asking how to build a local solar microgrid to not be reliant on the utility as that is what they care about the most.
  - Electricity bills: SDG&E has a 60c/kWh during peak time. Rates are a huge part of people's lives and their bills, and it is going to get worse.
  - Showcase the effects of climate change in different scenarios, people are willing to pay more to have a more resilient and clean energy system. Financial, environmental, and social footprint critical in the optimal investment plan.
  - Summary: Communities have concerns about resiliency and reliability, flooding, and metering, but in general customers are open to get to know about renewables. A lot of their goals are what researchers and industry are trying to do, but we need to give them the proper information and why they might want to make those decisions. They can be made to realize the goals are aligned!

- <u>Question/comment:</u> Energy justice seems to be focused on when electricity is flowing, what about when there is an outage? Have you considered terms of energy justice during outages?

  <u>**Discussion:**</u>

  - A lot of older areas/lower income have overhead power lines and normally experience more outages.

        - Community shelters (microgrids) can be built for a safe haven
        - Cooling/heating centers as microgrids, e.g., resiliency hubs
    - To get around legal and regulatory issues with adding renewables, Ann Arbor is building a redundant distribution network in areas with low reliability.
        - City will own renewables and storage and run redundant wires to connect low reliability networks.
        - Not hardening the existing network because of a poor relationship with the local utility.
    - DOE Program called GOPHURRS to support underground distribution systems.
        - https://arpa-e.energy.gov/technologies/programs/gophurrs
    - Energy burden is defined with respect to the cost of energy bills, but there is also an outage aspect. Maybe a social vulnerability index might work.
        - Social scientists are looking to quantify pieces of these, e.g., the energy poverty gap which is difference in when a lower income person turns on their thermostat vs. a higher-income person.
        - Pushback in Spain was that energy poverty is just poverty, there is no difference. There are some problems related to energy that need to be addressed, e.g., more energy inefficient households, less awareness, less access to capital markets to invest in efficient appliances.
            - Justice40 uses the environmental justice definition to enable the EPA to regulate; does the power system need an official definition of energy justice?
            - Not useful in terms of a theoretical framework, but by breaking it into pieces can then write legislations around it. How do you define which 40% of Justice40 count, how do you direct the money towards these communities, etc.
    - Summary: Power researchers need to use outputs in social science research to drive proper indices and decision making.
- Question/comment: When there are outages, how do we define the correct solution to provide electricity to the right loads? Also, when you provide knowledge the power is going to go out, people do not want to go to the heating/cooling center (or leave their residence before hurricanes).

  Discussion:
    - People leave their homes more frequently for power outages than disaster warnings
    - Collateral impacts: E.g., a hospital has no problem with outages (backup generators); however, hospital personnel need a way to leave their house to get to the hospital during an outage.
        - Mobile storage units (e.g., vehicle-to-vehicle energy transfer) could be sent by the hospital to charge local batteries at the hospital personnel's home, which then can run the heating/cooling system, vehicle battery, charge phone, etc.
    - Focus on four pillars of equity: structural equity (historical, cultural dynamics that led to inequity), procedural equity (create inclusive and accessible processes for clean energy programs), distributional equity (fairly distribute benefits across communities and between

nations), and inter-generational equity (how to consider the impact on future generations and how our choices affect them)

- Question/comment: The general needs of consumers have not changed much over time, however the generation, transmission, and distribution systems have drastically changed in the last quarter century. Give consumers the rights and privileges of generators.

  Discussion:

  - Less than 3% of consumers participate in markets.
  - Demand flexibility benefits other people too; even some consumers doing nothing they benefit from other consumers offering flexibility into the market.
  - People do respond to certain signals (e.g., critical peak pricing), but most electricity policies are not salient enough.
    - Most people would need more motivation (e.g., climate, ethical, etc.) as a driver
    - Need smart devices or aggregation to drive this.
    - DR signals can be unequal: CPP was an effective way to shift demand as it makes the signal very visible, but is also more unfair than other mechanisms.

- Question/comment: Consumers do not trust utility companies. Utilities do not trust consumers and want much more control over the interconnection. If the trust is diminished, it is going to be difficult to have demand side control. Are there any studies on energy trust?

  Discussion:

  - Focus on trusted members of the community that knows about how to connect the consumer to the right programs, navigate utilities, etc. Find champions within the community and can build trust with the utility. Need to build the relationships via people you trust (trusted advocates).
  - If the only interaction you have with a utility is paying your bill for a decade, you have a negative view of that entity. Utilities are spending money on PR and outreach to build trust within the communities.
  - Energy Communities in Europe to build trust, create local stakeholders, and contribute towards a clean energy transition.

Appendix F: Scribe notes from discussions on Topic 4

Topic #4: The Impact of Weather Hazards on the Grid and Risk Assessment and Mitigation

Panel Moderators:

Andreas Ulbig (RWTH Aachen, Germany)

Sara Mullen-Trento (EPRI, USA)

Panelists:

Auroop R. Ganguly (Northeastern University, USA)

Mladen Kezunovic (Texas A&M University, USA)

Elina Spyrou (Imperial College, UK)

David Kroeger (TU Dortmund, Germany)

Scribes:

Payman Dehghanian (The George Washington University, USA)

Sara Eftekharnejad (Syracuse University, USA)

Auroop R. Ganguly of Northeastern University first discussed the "**three grand sustainability challenges and the role data sciences**". Three main ***research questions/challenges*** were discussed:

1) The "*global weirding challenge*": What climate change and variability imply for weather extremes impacts on critical infrastructure?

- Heatwaves, regional warming, and persisting cold patterns (colder cold streams and hotter heatwaves) are what will be expected more frequently and with higher intensity in the future, and the uncertainty in such realizations is larger than what is generally perceived.

2) The "*infrastructure adaptation challenge*": How could earth sciences and data sciences jointly address gaps in translating to scales relevant for infrastructure?

- Explainable AI and computer vision can help translate global climate models to stakeholder needs and scales.
- ML informed by process understanding helps inform downscaling and uncertainty.
- Explainable AI (e.g., explainable deep learning) could address key gaps in climate science and impacts assessments, offering insights on global climate indices and regional weather resources. There are existing challenges of whether the generated datasets can be trusted.

3) The "*lifeline networks risk challenges*": How engineering principles and graphical or network science models inform risk assessment or mitigation.

- Existing examples have demonstrated comprehensive multisector climate risk management for a case of urban/regional transport systems, and how network science guided by engineering principles can inform lifeline railway network resilience under climate loads.
- It is critical to show how failures cascade in critical networks (e.g., airports and railway systems, power systems) that can be compounded with cyber threats, and is also important to be able to recover from those cascades at a regional scale.

Mladen Kezunovic of Texas A&M University discussed "**Predicting, Managing, and Mitigating Risk of Forced Outages through ML/AI**".

In particular, the following research challenges were emphasized:

- How in principle outages occur and what their impacts are in our society? He explored the different modalities (causes) of power outages emphasizing the leading role of weather/tree-caused outages. The wide-ranging (low, moderate, high, catastrophic) impacts of outages in the society were also discussed.
- How can outage risk prediction improve resilience? A solution could be to establish a link between outage risk indicators and resilience behavior of the network performance.
- To address the data challenges of predicting outages, one solution is to leverage data available from many sources. He explored the correlation between outage causes and the related data (on vegetation, utility measurements, weather forecasts, network assets, social media, lightning data, etc.). Depending on the choice of the hazard being studied, data from related sources should be carefully used.
- How to assess impacts in temporal and spatial scales? Probabilistic spatial-temporal risk assessment could be important in future mitigation strategies. A framework for state of risk (SoR) prediction was introduced that is realized through the integration of models for hazard characterization, vulnerability assessment, economic impact quantification. The SoR prediction analysis framework could use data of different resolution and for different applications of variant granularity. An example use case of the proposed SoR framework around distribution vegetation management was presented.

In summary, a number of ***research questions*** were highlighted:

- Is the State of Risk (SoR) prediction using ML/AI, a *transformational* opportunity for outage risk assessment, management, and mitigation?
- If we can *predict* forced outages, what are the pro-active opportunities for control, planning and protection management and mitigation actions?
- How to assess impact of the outage *prediction* at different spatial (component, system, region) and temporal (minutes, hours, days) scales?
- How the *data-driven* models can be correlated with *physics-based* models to assess outage SoR impact on resilience of other critical infrastructures
- How the social, behavioral and economic sciences, decision and control, computer/data, and geo sciences intersect around outage SoR prediction?

Elina Spyrou of Imperial College, UK discussed "**Fundamentals from Risk Analysis and Science**" on how can we join forces with the risk analysis community.

There is a relationship between "risk" and "resilience": "the [un]resilience of a system is the risk of [not] achieving desired functionality, during a specific time, following an event". The risk cycle was introduced that consists of identifying hazardous weather events, assessing risks, responding to risks, monitoring risks, and reporting risks.

Several open ***research questions*** were presented around each item of the risk cycle:

- How can we *Identify hazardous weather events?* Examples from the current practice raise open questions on how to identify weather hazards:
    - For an evolving power system, it is not clear how much historical data could be helpful and how much simulated data could support identification of hazards.
    - Considering the impact of climate change on weather events.
    - While accounting for compound effects?

- How can we *assess weather-induced risks*? This needs an understanding of the desired functionality of the system and how to assess the consequences of deviating from the desired functionality. The main open questions in this front are:
    - To monetize or not the consequences? If yes, research needs on value of lost load and corresponding model enhancements are highlighted. If not, multi-criteria decision frameworks might work.
    - How to consider multiple stakeholders and include them in risk management processes?
    - And how procedural and distributional equity can be incorporated in risk management processes?
- How can we *respond to risks?* In deregulated markets, the ability to trade risk affects decisions to mitigate vulnerability of power system infrastructure to extreme events. The main open questions are:
    - What would be the effective market or policy instruments to manage multiple hazards and cumulative impacts of events, taking into account risk attitudes and action timelines?
    - What would be the effective market or policy instruments to credit resilience-enhancing technologies and charge agents benefiting from/demanding resilience, taking into account risk attitudes and action timelines?

It was highlighted that risk management has always been complex, and therefore, some open questions are long lasting, with new questions emerge as the technology mix evolves, climate changes, deregulated markets mature, digitization progresses, and public dialogue identifies new priorities.

David Kroeger of TU Dortmund discussed "**The role of weather simulations and databases in energy systems modeling and analysis**".

He first discussed the grid development in Europe, where a recent European 10-year network development plan was accompanied by 3 weather years of data, motivating the question "are single or a few selected weather years sufficient for robust planning?".

- He discussed weather data for energy systems analysis, ranging from historic (easy to obtain, often limited), semi-synthetic (mixture of both worlds, occasionally used), and synthetic (challenging, but powerful) data.
- He then delved into assessing the impacts of weather-induced uncertainties, where historical weather data could be fed into a synthetic weather model, impacts on energy system being quantified, leading to evaluation methods and metrics.
- He presented that a research conducted by his group indicated that for an effective and reliable analysis of an energy system capturing weather-induced uncertainties, 950 weather years were necessary.

He then introduced open ***research questions*** on weather data analytics centered around:

- Multivariant distributions of data and their implications on probabilistic studies. It is critical to capture the dependencies between various parameters.
- Trade-off between cost and reliability should be considered.
- Probabilistic contingency analysis compared to traditional N-1 or N-k contingency analysis could be approached.
- IPCC trends should be monitored and applied.

- How to identify the Representative weather candidates to reduce the number of weather years needed.
- How to effectively communicate the research outcomes to stakeholders?

Summary of Panel Discussions and R&D Directions:

- ***Outage Prediction:*** Outage prediction should not only account for the prediction of the outage volume (loss of load quantity), but also the prediction of the location of the failure(s). This indeed depends on the decisional contexts: different spatial and temporal needs and requirements. The immediate question is how to gauge the prediction model fidelity for different applications that need the outage prediction information.
- ***Extreme Events:*** Extreme events and catastrophe modeling should be linked to the vulnerability of the equipment with respect to the parameters of the extreme events. The use of fragility curves to be designed with considerations of extreme events was discussed. Questions were raised on whether vulnerability assessment on component basis can be generalized?
- ***Resilience and environmental justice:*** Hazard, vulnerability, and damage exposures can and should be linked to environmental justice: how should damage exposure and risk mapping be done carefully with considerations of individuals and equity, ensuring that the risk map is used and decided upon later correctly and reasonably, remains an open research question.
- ***Heterogeneity in Utility Practices:*** It was discussed that while the *methods* can often be generalized, specifics such as decision time horizon mandate careful considerations and precise understanding. Heterogeneity in utility industry practices regarding available databases for risk management adds another layer of complexity.
- ***Outage Prediction Scale:*** As we move toward a more flexible grid, should the scale of the predictions be smaller (spatially to the level of solar panels and temporally for every minute)? The decisional context and the value of the information provided to an end-use application drive the scale of the predictions. Decisions often require data and information that need to be received from a variety of new grid-edge entities (e.g., aggregators), which adds another layer of delay and complexity on the spatial and temporal scale of predictions.
- ***Solution Complexity:*** It is generally not recommended to apply very complex models and solutions on simplified systems. Instead, simple solutions that can work in real-world large-scale systems should not be forgotten. It was noted that as we are moving away from a static view of the system to a more dynamic view, increasing complexity of the solutions is unavoidable. New approaches that can capture this complexity effectively, while including (learning and adapting to) the dynamic features of the system and the conditions it is exposed to should be sought after. Complexity is favored if it brings value.

Appendix G: Scribe notes from discussions on Topic 5

Topic 5: Complex interactions between the electric grid and other critical infrastructures

Panel Moderators:

Mark Lauby (NERC, USA)

Norela Constantinescu (ENTSO-E, Belgium)

Panelists:

Ben Kroposki (NREL, USA)

Yury Dvorkin (Johns Hopkins University, USA)

João Peças Lopes (INESC, Portugal)

Scribes:

Yuanyuan Shi (University of California San Diego, USA),

Amritanshu Pandey (University of Vermont, USA)

Presentations

Ben Kroposki (NREL, USA)

U.S. 2050 climate goals will be met by solar + wind (likely to comprise 60% of total capacity)

- Electrification is a primary driver of most changes in the future electric grid.
- Energy storage is necessary and needs to grow from 25 GW today to roughly 250 GW (by 2050)
- Meeting storage goals with just batteries might be tricky; multi-energy systems integration is one solution.
    - Integrate multiple energy systems
    - Incorporating customer behavior into models is critical
- Research needs:
    - Understanding interdependence
    - Modeling and simulation of cross-sector energy systems
    - Optimization across energy domains
    - Value quantification of integrated energy
    - Integration of customer behavior into the operation of the energy systems

Yury Dvorkin (Johns Hopkins University, USA)

- Research into modeling deep uncertainty is important and requires a better understanding what factors will affect both planning and operational decisions. Such factors are typically hard to model or infer from data, but their impact on planning and operational decisions could be great. Examples include: technical and cost characteristics of long-anticiapted technologies such as long-duration energy storage and/or small-scale and modular nuclear power plants can drastically shift CAPEX/OPEX trade offs and affect system resiliency (e.g., in both ways: first by providing new source of flexibility to relieve stress from existing assets and/or repurpose them; and second by unlocking new vulnerabilities ranging from supply chains to operational constraints. There is a need to itemize current and emerging sources of "deep uncertainty" and have a robust series of "plan b" actions in case of one or multiple of them materialize. The primary challenge is that the cost of mitigation (or adapation) to this deep uncertainty is hard to estimate

- In addition, resilience of the future grid will require an overhaul of current operational principles, which are more dominated by principles aimed at a conventional, fossil-fired power grid:
    - Weather-driven versus N-k contingencies: as penetration of weather- and climate-dependent resources such as solar, wind, and hydro generation increases, it is more important to devise reliability standards that account for weather and climate variables; this need extends beyond a "plain" statistical analysis of output variability and must have a pro-active integration of weather and climate variables. Another important limitation of the current practice is the ability to integrate long- and short- term effects of weather and climate dependencies, which are not typical for conventional fossil-fired geneerators.
    - Modeling damage through the Value of Lost Load (VoLL) and Expected Energy Not Served (EENS) is not sufficient; it will be more important for puture power grids to have a more granular understanding of power grid impacts – both locationally and per customer, a capability which is currently lacking. This will require both more granular metrics (where electricity vulnerable customers are located? what is their exposure and specific vulnerabilities are? how to compare different consumers in terms of vulnerabilities) and more customer-oriented response and recovery strategies.
- Compounded threat analysis is an avenue that should be explored. This concerns more complex threats, which include a combination of the extreme weather and "deep uncertainty" events as well as malicious actions of adversarial actors (e.g., foreign powers, domestic and foreign non-state players).
- Should consider integrating Computable General Equilibrium (CGE) models with other domain-specific models and vulnerability models, which is a mechanism to understand nuanced impacts of the threats and supply interruptions on specific economic sectors and customer groups.
- Three key messages for ensuring resiliency of future power and other infrastructure system operation solutions under uncertainty: economy-wide model coupling, modeling of deep uncertainty, and including societal behaviors

João Peças Lopes (INESC, Portugal)

- Analysis of interdependent systems critical (In Portugal, its gas+electric+hydrogen)
- Portugal has 60% Renewable Energy Standard (RES) (of the total capacity of 20GW); Spain is very similar; minimal supply capacity from France (around 3.5 GW)
- Portugal's installed capacity is likely to double in the coming years
    - 2-3 TWh of excess energy anticipated
    - Seasonal storage necessary (store in summer and spring, use in Winter)
- Assessing the security of supply under uncertainty via Monte Carlo simulation
- The main challenge is that the complex and integrated energy systems include integrating and managing advanced digital infrastructures, designing and operating 100% renewable energy for green hydrogen and developing digital models for emerging technologies, and the integrated optimization of multiple networks.

Discussion Sessions:

<u>Q1 - Where does the hydrogen come from?</u>

- River, Ocean? Is desalination a concern

- Quality of water is critical.
- More investigation into green hydrogen is necessary
  - Currently, only 1-2%
  - Cost reduction is a challenge, and coordination with the power grid could be an important value add if hydrogen is used for such services as flexibility reserve and long-duration storage
  - Better technologies for hydrogen are required
- What if we cannot bank on hydrogen
  - Is something else needed? Should we look at other technologies too?
  - There is no one-fits-all solution when it comes to power grid decarbonization and while hydrogen presents a very sensible solution, it has its own challenges – both technical and economic, and therefore from the viewpoint of risk management, we need a portfolio of technologies with a shigh degree of substitutability across various functions they could perform.
- Water is essential. It's not everywhere. Piping hydrogen can be hard
  - Very dependent on the geography; San Antonio's population is likely to double, shortage of water is possible; building pipelines from the Gulf of Mexico will cost Billions of dollars
  - More research in Energy Nexus is necessary
- Europe has decided to go all into H_2. No longer a question of whether hydrogen is the future in Europe
  - Shell wants to build a 200 MW Hydrogen plant
  - The university cannot get vendors to supply 100 kW units due to the very high demand.
- Where the hydrogen will be used: In Europe, chemical industries are likely to use the H_2 to decarbonize; green steel can use up to 10 TWh per year

<u>Q2 - The energy mix of the future. Is anyone answering what the future energy mix should look like?</u>

- Resilience is important. What energy technology is most risk-averse?
- There needs to be more studies on the evaluation of multi-energy system risks. Very little understanding of risk due to multi-energy systems. Lots of opportunities on that front: 1) what are the interdependence and additional vulnerability introduced to the system via the coupled systems; 2) how does failure on the electricity grid on the other infrastructure
- Large offshore wind projects in the North Sea with onsite H_2 production; the aim is to send H2 to the shore via pipelines
- Very happy that US Bipartisan Infrastructure Law (BIL) and the Inflation Reduction Act (IRA) created an atmosphere that supports a technology-neutral approach
  - The central decision-makers shouldn't decide the choice of future technologies

<u>Q3 - What about software tools, modeling, and planning methods for multi-energy systems</u>

- There have been a lot of advancements in the modeling and simulation of multi-energy systems in the last 5-10 years e.g. include national lab tools from National Renewable Energy Laboratory (NREL) and Pacific Northwest National Laboratory (PNNL). The Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS) from PNNL is one such example.

- The real challenge is datasets. Not enough currently exist for multi-energy systems modeling and simulation
- Another challenge is that current datasets are not updated. Often, academics end up using obsolete datasets for their analysis.
- We need simulation software of different time-scales:
    - Fast transient: electronics, circuits
    - Slow simulations: fuel cell and power system planning
    - Challenge on how to let people be aware of the existing simulation tools, get people to use and maintain these tools, and promote them as a standard

Q4 - How much electrification is possible? How about the industry being electrified? What kind of trends are we observing there?

- There are some solutions for industries that are thought to be "hard to electrify"
    - Example: Shipping (during idling) in Portugal is likely to electrify; when on-shore ships are likely to plug into on-shore outlets during idling (ships can consume anywhere from 5-15 MW during idling)
- Almost all industries are looking at how to decarbonize;
- Chemical and steel are some of the hardest industries to decarbonize; these are open challenges. The chemical industry is hard to decarbonize; flexibility from multi-energy infrastructure may be the solution
- There is a difference between "producing/using carbon atoms" versus "releasing those into the atmosphere"; we want to prevent the latter.

Q5 - Question about the modeling of the coupling using Computable General Equilibrium (CGE) models. How can we better capture/understand the behavior of agents?

- There are challenges/drawbacks with CGE models but the model can provide lower bounds on certain risk analyses and overcome some limitations of classic Value of Lost Load (VoLL) and Expected Energy Not Served (EENS) analysis
- The need for interdisciplinary efforts to tackle challenges in the field of multi-energy systems. Electrical engineers alone cannot solve all problems.

Q6 - What motivates other sectors to couple with the electric grid?

- One of the big challenges is to figure out who will build and finance the transition to new energy system. For example, it is easy to say that hydrogen can decarbonize, but harder to show when you dig into the details of who will pay for it and who will build the pipelines. In short, people haven't really mapped out the details of decarbonization.
- Some easy solutions exist. For instance, in Europe, at the distribution level PVC pipes transmit natural gas; the same infrastructure can be used for H_2. At the high-volume transmission level, minimal changes can be made to use the gas infrastructure to transport H_2.
- When discussing multi-energy systems, the agents are minimizing their cost function; regret, and cost under uncertainty

Audience Comment - A big challenge is battery disposal.

Q7 - Coordination between electricity and hydrogen;

- It really depends. NREL has done many studies on this question. In the U.S. building pipelines is easier than transmission lines; so independent of economics, pipelines are the most likely choice
- Europe is coming up with many regulations that strictly dictate temporal correlation for green hydrogen; where electrolyzers are placed etc.

Q8 - Regarding the Modeling of Multienergy systems.

- Time-scaling the modeling interdependencies between different multi-energy systems is hard and an open research question.

The solution for one system modeling at a one-time scale may not be good to others, for example, models for predicting day-ahead gas price and weather conditions, and then integrate these predictions to plan better both gas and power network together

Appendix H. Scribe notes from discussion on Topic 6

Topic 6: The education and training fundamentals for the realization and support of a resilient society

Moderators:

Stratos Pistikopoulos (Texas A&M University, USA)

Luis Olmos (Pontificia Comillas University, Spain)

Panelists:

Charlie Smith (Energy Systems Integration Group, USA)

Siddharth Raju (University of Minnesota, USA)

Maria Michael (University of Cyprus, Cyprus)

Alexandros Chronis (National Technical University of Athens, Greece)

Scribes:

Sijia Geng (Johns Hopkins University, USA)

Mladen Kezunovic (Texas A&M University, USA)

Summary of Presentations:

- **Charlie Smith: G-PST Pillar-3 Workforce Development**
    - The Pillar 3 of the Global Power System Transformation (G-PST) Consortium activities aim to facilitate the development of a diverse and inclusive workforce that can support deep decarbonization of the electric power sector globally.
    - Its focus areas include: 1) Develop course material on 'forward-looking' topics for university education and training industry professionals; 2) Work with local university partners for delivery of the material (run 'train-the-trainer' where necessary); 3) Promote gender diversity in the workforce.
    - A teaching agenda group was set up in 2020, consisting of academics from seven universities across Europe and North America. They identified 'forward-looking' topics where education/training is essential but lacking and produced a teaching agenda that outlines over 90 'forward-looking' topics under 9 subject areas.
    - Six founding system operators and six other system operators prioritized the topics under each area in the teaching agenda based on their needs and the skills gap they face. Collective priorities can be found here: https://globalpst.org/category/pillar/pillar-3/.
    - Course materials on several topics are available for download, each topic has 3-5 hours of recorded lectures, lecture slides, and exercises. There are virtual office hour sessions for each topic to engage with stakeholders. The course material can be adopted into existing curriculum and is suitable for virtual teaching or flipped classroom format.
    - G-PST hosts multiple webinars which are posted online, and motivational videos that highlight the successful journey of women professionals who are leading transformative change in power sector to inspire more women to join the power sector, upskill and take up leading roles.
- **Siddharth Raju: Building A Robust Workforce in Electric Power Engineering by Democratizing Technical Education**

- There is a massive deployment of wind and solar in order to achieve the goal of net zero by 2050. However, enrollments in EE majors are sharply declining.
- We propose multiple pathways that feature employment preparation education (EPE) as the solution, which integrate industry support and pipeline courses spanning high schools, community colleges, and universities (BS, MS, PhD).
- Such programs are appealing to students due to high expected earnings from a professional degree and lower tuition for community colleges.
- CUSP includes universities that have come together to use, collectively evolve and promote the curriculum developed at the University of Minnesota, Twin Cities. The vision of CUSP is to provide all the resources an instructor needs in teaching his/her own courses in the field of Electric Energy Systems with an emphasis on sustainability. This effort has been funded by various organizations including NSF, ONR (Office of Naval Research), NASA and EPRI and is totally free of cost under the Terms of Use conditions.
- An NSF workshop on Crisis in Power Engineering Education: A National Security Concern was held in Minneapolis on October 21-22, 2022.

- **Maria Michael: Intelligent Critical Infrastructure Systems - Education & Training**
  - Critical infrastructure systems (CIS) are assets or systems that are essential for the maintenance of vital societal functions and are often modeled as cyber physical systems (CPS). CIS are expanding, digitized and becoming more complex. Frequent equipment failures, malicious attacks, natural disasters, and unexpected events lead to degradation in performance/breakdown and interrupt 24/7 service.
  - The objectives of the M.S. Program are: 1) Transfer scientific knowledge on the research and innovation challenges and solutions of modern intelligent CIS; 2) Create a competent workforce to be recruited by local/regional authorities and international companies.
  - The learning outcomes for the graduates of the program are: 1) Deal with particular CIS challenges, understand the specific technical and management features, and the specific risks and security issues related to the considered CIS; 2) Apply innovative Information and Communication Technology (ICT) techniques to address monitoring, control, management, and security of CIS at the technical, managerial, and policy level; 3) Conduct both theoretical and applied research.
  - The laboratory facilities include KIOS laboratory infrastructure & CIS testbeds (Power Systems, Water Systems, Transportation Systems, Cyber Security, Telecommunications Systems)
  - Some main takeaways are: 1) Students appreciate the blend between theoretical and ICT skill-development courses; 2) Hands-on application courses (in the lab) connect theory with practice; 3) Innovation/Entrepreneurship experience and development of soft skills are highly desirable; 4) Can supplement with specialized courses or training material on particular application domains such as Power & Energy; 5) Additional technological or digital tools are needed to facilitate remote/virtual lab support; 6) Need for new educational methods for blended/hybrid education in engineering disciplines.
- **Alexandros Chronis: Navigating the Digital Energy Transition: Emerging Skill Needs and Educational Tools**
  - A multidimensional method was developed to address skill mismatches between the industry and the education and training provider.

- The key areas that present skill gaps towards digitalization include data management and analysis, big data, cybersecurity, and programming and development competences.
- The power sector showcases the biggest skill gaps. Possibly linked to the increase in distributed energy resources, smart grids, etc.
- Apart from the technical skills and competencies, transversal, business, and green skills are very important in the energy sector.
- University curricula, online training platforms as well as industrial training programs cover several aspects of digitalization yet there is plenty of room for improvement to foster digital transformation.
- Educating students at a young age about energy systems can increase awareness and engagement, which can support the energy transition.
- Some main takeaways are: 1) New technical tools and educational methods are needed; 2) Physical hardware-in-the-loop (HIL) simulation is an efficient educational tool; 3) Remote/virtual lab can support the educational process; 4) Jupyter notebooks are promising interactive tools that support student understanding and experimentation; 5)Advanced educational methods support student engagement and learning while providing meaningful experiences to students: application in power systems can be further promoted; 6) The importance of digital tools for education/training is increased during the pandemic. These tools can complement the educational process in traditional methods.
- The IEEE PES task force on innovative teaching methods for modern power and energy systems aims to investigate, create, and promote the use of innovative teaching methods and materials in modern power and energy systems.

Summary of Discussions:

- **Question 1:** A lot of my students are interested in going into computer science because the salary is high. Do we need to change the power curriculum to adapt to what the students like, or do we need to make the power curricula more appealing in some other way?
- Responses:
    - EV industry has a higher payment which could possibly be helpful in addressing this problem. We need to make the power program more attractive. It’s helpful if people see more discussions about the challenges we are facing now and see more posts on solar PVs and wind farms in mass media. Also, some interesting topics in power systems belong to other departments instead of EE. We need to take them back somehow and make the EE program more interesting.
    - It is important that we align the program with the industry’s need, for example, digitalization connects well with CS and ML. We should teach AI/ML, cyber security, and simulation skill, which have a place in the industry and allow students to gain skills in this area.
    - Salary is a market-related issue. The salary needs to be increased to solve the problem. Besides, the young generation needs to be exposed at an early age at secondary or even pre-secondary school.
    - The salary needs to reflect the importance of the work.
    - In a regulated industry, the cost of raising the salary rolled over to the rate eventually. There is a real struggle in trying to increase the salary for engineering professionals in a regulated industry.

- **Question 2:** More and more people are working on optimization, ML, etc. what is it that makes power system power system?
- Response: There is certainly theoretical aspects and applied practical needs. The future 100% renewables-based power systems are very different than the current systems.
- **Remark 3:** In Portugal, there is a tremendous shortage of power system engineers because people don't realize that for the decarbonization of the economy, power and energy systems skills are required. They don't understand the importance of the work. It is necessary to make an effort at the very beginning, starting as early as high school or the first year of college, to make the students understand what power systems aim for. We should bring industry to the school to make them know the importance of power system engineering.
- **Remark 4:** The number of power engineer students at the University of Michigan has not dropped over the last 15 years. We offer in the undergrad power systems course, power electronics, and machines. The numbers of the latter two courses are limited in terms of the sections we can put into the labs. In power systems, it has been stabled to 35-40 students. Michigan is in an industrial area because of the automotive manufacturing industry, and maybe that influences students' choices.
- Responses:
    - From the data we collected, there have been a handful of universities that do not seem to be affected by the trend, one of them is the University of Minnesota, and another case is TAMU. However, that's only a handful of universities. A controversial measure in preserving power students is to cap the number of enrollments to CS.
    - We also don't face this problem in Cyprus, there is a great need for power engineers. Indeed, there is hype in AI. There is a need but we need to make it to the prospective students about the needs in our area.
- **Question 5:** We do need a lot of power system workforce; we are not able to attract a lot of students to power system program. But we also thought that power engineer needs a lot of expertise from many areas, CS, chemistry, operation research, etc. My question is that, instead of developing and extending power system curriculum, can we inject courses from different departments?
- Responses:
    - That might be a little difficult given the specialization of power systems.
    - There are some new aspects, for example, meteorology and forecasting. There is some opportunity in cross-listing such courses.
- **Question 6:** Who do we want to educate and what is our goal? Power system engineer or engineer?
- Response: This is an interdisciplinary problem. The energy system of the future is not only on power system. We should look horizontally instead of vertically.
- **Remark 7:** We are talking about the need from the industry. I have a feeling it's us that define the need instead of the industry. Are we defining it correctly or not? Secondly, we are translating what we defined into a program that gets all these things into one head. I don't think that is the case. If the industry really wants to do data analysis, they hire some people from data analysis, and that person will interact with power system people. We need to rethink how we are trying to map what's going on in the world into the university environment. Thirdly, our main focus is our product, meaning, students. However, our schools are interacting backward. How far are we going? We are trying to attract the youth into something that is big. For example, religious organizations go out all the way from pre-K. There are specialized museums that can attract very little kids and expose them to amazing concepts and make them very excited.

- Responses:
    - Students in our classes love industry stories. We bring in people from the utilities, and from the public service commission, and we tell our own stories about industries. That motivates the students a lot. It's not just learning the power flow equations; it's hearing things that could go wrong in the industry. We also run short power system courses that go to the wider community in the university through the energy institute. There are lots of people such as social scientists who are interested in the issues that are related to energy transition but don't have a way of connecting to that.
    - This is a very good model. A model that we have is an interdisciplinary institute that takes master students from different backgrounds. The institute pushes them to think about policy, data science, etc., to know about the domain. It integrates research and training.
    - Specialization is going to go away; the need for multi-disciplinary skills is there. We need to get students from different domains and expose them to the curriculum.
- **Question 8:** What about the developing country? What is the best way to reach them and make a contribution?
- Response: This is also an important part of the G-PST activities. There is a "Communities of Learning" that are regional, scattered around the globe. One of the points of intersection of P-GST and those communities is through the Pillar-3 teaching agenda. The intention is to make the teaching materials available. After listening to the discussion, I think we should extend the coverage of the course material and expand the agenda and share it very widely.
- **Question 9:** What is the minimum packaged course that we can add to other degrees and can make ME/CS people know about power systems so that they can contribute to the power system field?
- Response: University has a very strict number of credit hours for undergrad so we can't fiddle much. For master/PhD students you can do a lot. When you go down the schools, they are also prescribed by the state. Where it can be done is teamwork, trying to understand from a very early age when you play the game as a kid and when you engage with others. People do not work well together across areas. Unless you know somebody, it takes forever to get on and speak the same language. I think we should restructure how education works. Remembering the old days in the 14 century when the minds got together and had workshops and talk about astronomy. They were educating each other and making progress.