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# Basic Research Needs to Understand the **Human Dimensions of Energy Systems**

## September 6-7, 2022 Workshop

Research Questions and Next Steps

## Acknowledgments

The National Renewable Energy Laboratory would like to thank everyone who participated in this event with a special thanks to those external participants who took time out of their schedules to travel to Golden, Colorado, to share their research. Their names and affiliations are listed below. A complete list of presenters and their bios are shared in Appendix A.

**Joana Abreu – TRC Companies, Inc.**

**Ronald Boring – Idaho National Laboratory**

**Bing Dong – Syracuse University**

**Michael (Misha) Chertkov – University of Arizona**

**Emiliano Dall'Anese – University of Colorado, Boulder**

**Daniel Eisenberg – Naval Postgraduate School**

**Emily Grubert – University of Notre Dame**

**Majeed Hayat – Marquette University**

**Patricia Hidalgo-Gonzalez – University of California, San Diego**

**Wan-Lin Hu – SLAC National Accelerator Laboratory**

**Enrique Mallada – Johns Hopkins University**

**Line Roald – University of Wisconsin, Madison**

**Jeffrey Schlegelmilch – Columbia University**

**Benjamin Sovacool – University of Sussex**

**Deepthi Vaidhynathan – University of Colorado, Boulder**

**Parth Vaishnav – University of Michigan**

# Background

Advanced energy technologies and informed policies are necessary but not sufficient to accelerate the energy transition at the speed required to meet our shared climate and energy resilience goals. To fully understand and implement integrated energy systems, we need to be able to model and analyze the complete system-of-systems, including the behavior of people interacting with and being impacted by energy systems.

## Purpose of Workshop

- Understand how human behavior and decisions affect the performance of energy systems with a focus on resilience and human well-being.
- Identify opportunities to improve energy system design to explicitly consider human behavior and well-being.
- Enhance our capability to model and predict human actions. Develop the ability to stress test these integrated systems.
- Identify or develop requirements and tools for more robust system designs that can be used for human-in-the-loop exercises and training.
- Identify opportunities for joint research, joint appointments, and collaboration.
- Guide internal investments and strategic hires.

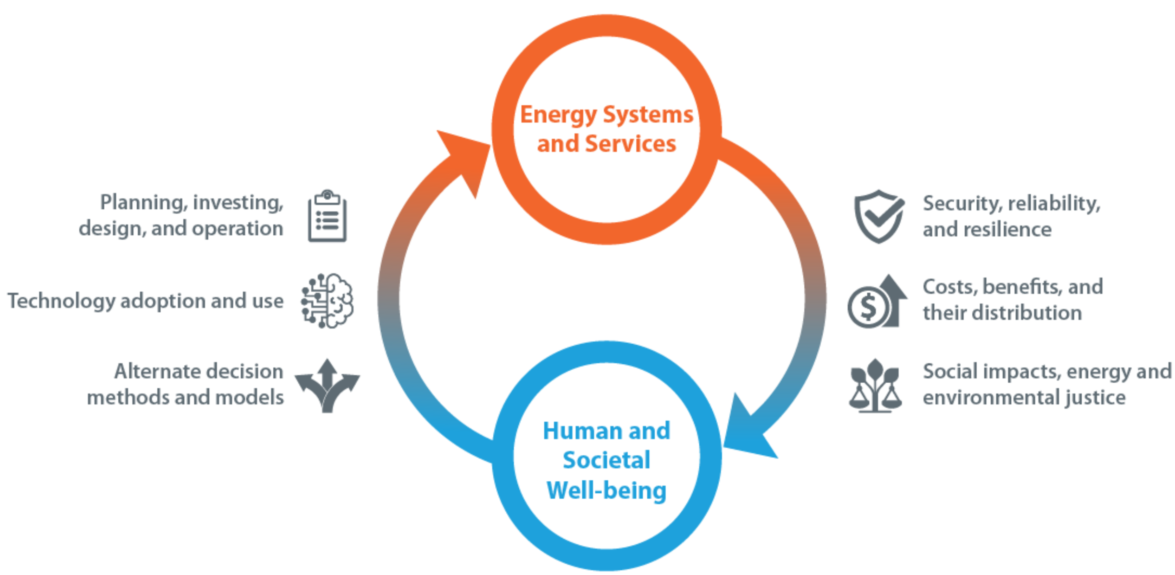


**Figure 1. Human Dimensions of Energy Systems**

Human behavior affects the performance of energy systems, which affects human well-being

## The Human Dimensions of Energy Systems

If society does not acknowledge the interdependent role that energy systems have with human well-being, especially for the most vulnerable among us, we are unlikely to meet our shared energy goals. It is critical that we build a more rigorous understanding of the human dimension of energy systems.

While human behavior is important and underrepresented within policy and design for all aspects of energy system performance, it is especially difficult to integrate the human dimension for the resilience of energy systems. One of the main reasons for this difficulty is the fact that events that test the resilience of our systems are rare, acute, and, therefore, difficult to build data-driven approaches for better understanding. This crucial gap in our understanding is compounded by energy systems' central role in societal resilience. When energy systems fail during disaster situations, human well-being is affected, often with the most vulnerable being impacted most severely. This is because energy systems are a keystone infrastructure that is central to the interconnected web of lifeline-providing infrastructures; yet these systems are not designed with this fully internalized. Therefore, the resilience-relevant components within the human dimension of energy systems are especially important to investigate.

To fully understand and implement more resilient and integrated energy systems, we need to be able to model and analyze a more complete system-of-systems, including behaviors of people interacting with and being impacted by energy systems. A better understanding of the human dimension of energy systems will aid in the design of more resilient systems and the chance to conduct energy research and system design with human behavior and well-being explicitly considered.

Human behavior can have significant effects on the performance of energy systems at all scales. During emergencies and extreme events, energy systems are likely to have a heightened sensitivity to human behavior. Before or during an extreme event, human decisions and actions, from the individual to the institutional level, will change the demand and priorities for power. Energy operators at different levels make decisions that impact the available power and its stability.

Today, energy resilience research typically ignores the impacts of human behavior in designing, optimizing, and operating energy systems. These impacts are growing as the grid evolves to include more electrified systems, distributed generation, controllable loads, and microgrids. Energy resilience research traditionally focuses on the power and communication networks but ignores the "human network" of actors that range from individual consumers and large governmental or corporate consumers to owners of distributed energy resources and operators of microgrids and distribution systems.

### *Workshop Purpose and Structure*

The primary goal of the Human Dimensions of Energy Systems workshop was to shape future research efforts and to explore the appropriate role for a national laboratory investigating the human dimensions of energy systems. The team discussed current and future research efforts, productive partnerships, internal investments, strategic hires, and funding opportunities. Opportunities for joint research, joint appointments, and collaboration were discussed throughout the event.

Most of the discussions were focused on the power system and the behavior of those interacting with and operating power systems with an emphasis on system resilience. The workshop focused on advances in modeling and analysis concerning individual and group behavior from an individual household scale to microgrids and transmission and distribution scales. Factors impacting environmental and energy justice were a reoccurring topic throughout.

The workshop and presentations were structured around four themes, but conversations were encouraged that included topics outside of these core areas:

- *Understanding, modeling, and simulation of human behavior in energy systems* – Exploring the role of the human network in energy optimization and control to achieve energy resilience.
- *Modeling of human behavior in technology adoption and optimization* – Exploring the human network in energy optimization and control to achieve energy resilience.
- *People-in-the-loop modeling, testing, and analysis* – Methodologies for analyzing and preparing for the impacts of the human network and decision-making.
- *Community energy transitions and justice* – Energy and environmental justice must be considered during the energy transition to ensure the benefits are shared by communities.

### *Priority Research Questions*

Several questions were identified during the workshop that require in-depth research and analysis. A multidisciplinary, multi-institutional approach will be required to tackle these questions, requiring collaboration between national laboratories, academia, government, and the private sector.

**Data collection and information science in support of modeling human behavior related to energy systems**

Modeling any dynamic system begins with careful observation and rigorous data collection. Many engineers are experienced systems modelers, but data collection is complicated when the systems of interest include the behavior of individuals or communities. Researchers need to carefully consider how best to collect these data. Key questions include:

- What social data do we need to collect to improve our understanding of energy demand, technology adoption, and other relevant human behaviors? How can we use this knowledge to appropriately influence energy demand and use?

- How do we best collect these data while maintaining individual privacy? (Longitudinal field research, focus groups, interviews, survey data, behavioral economics, etc.)

- How do we better understand and model human behavior and decision-making, and how should we use this knowledge to inform and shape energy system design and operation?

- For resilience-relevant behaviors, how do we capture the right data at the right time, realizing that these events are rare and acute? How do we design and support a resilience data collection system that persists for several years? Are there historic resilience-informing data already collected that are underutilized?

**Understanding, modeling, and simulating human behavior in energy systems**

To fully explore the resilience of energy systems, we need the ability to model human behavior and how actions taken affect the performance of associated energy systems. There are several difference forms for systems models to consider. Key questions include:

- How do we model human behavior and the interaction between humans and physical systems? How do we best model human behavior in these systems (agent-based models, Markov chains, Monte Carlo, stochastic DE)?

- What are the main factors, such as community composition and structure, culture and values, and access to resources, that affect social networks and human interaction with the grid?

- How do we ensure a desired level of performance in distribution networks with non-complying or malevolent human behavior?

- How do we design an incentive-based mechanism to shape behavior and steer the system toward the desired level of performance?
- How do we use the human behavior models to improve state estimation and load modeling/forecasting methods?

- How do we best use the integrated, system-of-systems models to inform operators, planners, policymakers, and other stakeholders?

- With respect to real-time decision-making in power systems, is it more important to model the human behavior of customers, grid operators, or both? What are the key differences? What are the most important aspects of decision-making for the operation and control of energy systems? What do we need to model and what can be ignored?

- Breaking out chronic behaviors from acute, do we need to combine theory from multiple disciplines—e.g., psychology, behavioral economics, sociology—and are there examples of how that's been done in a quantifiable, mathematical framework to date?
- If the decisions being made concern purchasing decisions and technology adoption, how do we best model individual and group decisions? Which technologies need to be considered, and do we need to model difference actors (individual consumers, business owners, utilities, etc.)?

**Systems-level methodologies to quantify the human impacts on resilience**

Human behavior and decision-making are impacted by several factors that are not familiar to most energy modelers, including mental stress, social norms, dissonance, situation awareness, and several factors. A systems sciences approach is needed to model the most important causal linkages between the performance of energy systems during disruptions, the impact of human decisions, the resulting impact on human well-being, and how this, in turn, impacts decisions made about the operation of energy systems. Key questions include:

- What are the most important drivers of human behavior during extreme disruptions that are most heavily influenced by performance of energy systems?
- How do previously unincorporated aspects of human behavior during disruptions affect potential decisions of grid operators and emergency operators and first responders?
- How does the pattern of life (dynamic mobility) of the population indicate their well-being during a disaster?
- How do we improve energy resilience through energy systems control, optimization, and analysis with human-in-the-loop?
- How do we use models to best understand and prepare for surprises and cascading events?
- How can systems-level methodologies more holistically incorporate the finer-level insights being generated across several scientific fields and endeavors?

**Quantification and modeling the impacts of energy systems on human health and well-being**

Energy justice has many facets; distributional, procedural, and recognition justice are the three most discussed. Quantifying the impacts of decisions of human health and well-being is a first step in considering the impacts of decisions made about the energy system. Key questions include:

- What are the key justice metrics? How do communities co-define these metrics with researchers?

- How do these justice metrics consider the impacts of climate change, natural and man-made disasters, and the accelerating energy transition?
- What are the roles of non-energy actors in energy justice (policymakers, insurance, zoning, urban planners, etc.)?
- What are the linkages between acute injustices (e.g., resilience) and chronic (e.g., affordability, ownership, access)? How is resilience of society interrelated with long-term well-being, and how does this interrelate with energy systems?

**Developing communities of practice to expand the impact of place-based research and analysis**

A community of practice (CoP) is a group of people who share a common concern, a set of problems, or an interest in a topic who come together to fulfill both individual and group goals. Communities of practice often focus on sharing best practices and creating new knowledge to advance a domain of professional practice. Our work on the human dimension of energy systems may benefit for leveraging communities of practice focused on the energy systems. Key questions include:

- How do we share best practices and create new knowledge to accelerate the energy transition and advance energy justice?
- How do we best expand the impact of our place-based technical assistance efforts by creating communities of practice? Are there ways to directly connect communities and facilitate community-to-community communication and learning?
- What data, technical assistance products, stories, and open-source models need to be collected and shared? How do we best make these resources available to interested communities, researchers, and others interested?
- What socioeconomic, geographic, energy system, and other data need to be collected on the communities served, and how can these data be used for future meta-analyses of place-based technical assistance that includes the human dimension?

### *Next Steps*

We propose a multiyear, multidisciplinary effort to develop new capabilities within our national laboratories, academia, and partnering organization that can then be applied to fully understand and positively impact the human dimensions of energy systems. Investments in this effort will come in many forms, including internal investments and support from local, state, and federal agencies and associated nonprofits that support energy research.

- *Internal investments* - A key first step will be the funding of a Transformational Lab-Directed Research and Development (T-LDRD) effort at NREL. This internal investment will run from Fiscal Year 2023 through 2025. The T-LDRD will focus on human behavior and decision-making during energy systems disruptions and how these decisions affect system resilience and human well-being.

- *Collaboration* - The groups represented at the workshop are actively pursuing opportunities to collaborate and pursue joint research opportunities. This collaboration will take many forms, including the develop of joint proposals, joint appointments, and the mentoring of staff or students across institutions. Periodic in-person and online workshops will be held in the coming years to support collaboration.

- *Publications* – Technical reports, conference proceedings, and peer-reviewed papers will be developed to share the findings of our collaborative research. Our researchers will seek out opportunities to effectively communicate the impacts of this joint research with partners in industry, academia, government, foundations, and the public.

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# Appendix A – Speaker Bios

The workshop was a success thanks to the attendees and the excellent presenters. We all benefited from hearing from and discussing the work of this group.

## Joana Abreu – TRC

Joana Abreu has over 15 years of experience in demand-side management, energy efficiency, and sustainability. At TRC, she specializes in demand-side management, integration of distributed energy resources, strategic planning, program design, regulation, and behavior science. Before joining TRC, she was the program manager for demand response at Eversource, in Massachusetts, New Hampshire, and Connecticut, including commercial and industrial (C&I) interruptible load, EV and electric vehicle supply equipment demand response pilots, residential and C&I storage, and residential Bring Your Own Thermostat programs. Before Eversource, she was the human factors lead at Fraunhofer Center for Sustainable Energy Systems, conducting applied research for National Grid, New York State Energy Research and Development Authority, and the Massachusetts Department of Energy Resources. She was awarded a National Science Foundation grant for critical resilience of electrical systems.

## Douglas J. Arent – National Renewable Energy Laboratory

Dr. Doug Arent focuses on strategic public and private partnerships with NREL to transform energy economies at speed and scale across the globe. Arent has worked in research on energy and sustainability for more than 30 years, publishing extensively on topics including clean energy, renewable energy, power systems, natural gas, and the intersection of science and public policy. Previously, Arent served on the American Academy of Arts and Sciences Steering Committee on Social Science and the Alternative Energy Future, and he was a member of the National Research Council Committee to Advise to U.S. Global Change Research Program. Arent has a doctorate from Princeton University, an M.B.A. from Regis University, and a Bachelor of Science degree from Harvey Mudd College in California.

## Andrey Bernstein – National Renewable Energy Laboratory

Dr. Andrey Bernstein received his B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from The Technion – Israel Institute of Technology. Between 2010 and 2011, he was a visiting researcher at Columbia University. From 2011 to 2012, he was a visiting assistant professor at the Stony Brook University. From 2013 to 2016, he was a postdoctoral researcher at the Laboratory for Communications and Applications at the École Polytechnique Fédérale de Lausanne in Switzerland. Since October 2016, he has been a senior researcher and group manager at NREL. His research interests are in the decision and control problems in complex environments and related optimization and machine learning methods, with application to power and energy systems. He leads the energy systems control and optimization group in the Power Systems Engineering Center.

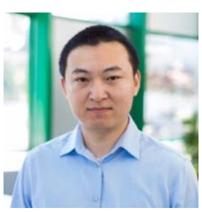
## Ronald Boring – Idaho National Laboratory

Dr. Ron Boring is a distinguished human factors scientist and department manager at INL. He has led control room modernization and human risk efforts for a variety of national and international partners. He was the founder of the human systems simulation laboratory at INL and led development of prototyping tools such as the Advanced Nuclear Interface Modeling Environment (ANIME) and human factors evaluation methods like the Guideline for Operational Nuclear Usability and Knowledge Elicitation (GONUKE) to support control room development at U.S. utilities. He has developed the Human Unimodel for Nuclear Technology to Enhance Reliability (HUNTER) method, which provides a digital human twin for risk modeling. Boring has a Ph.D. in cognitive science from Carleton University. He was a Fulbright academic scholar to the University of Heidelberg, Germany, and holds the honorary title of Fellow of the Human Factors and Ergonomics Society. He has published over 300 research articles in a wide variety of human reliability, human factors, and human-computer interaction forums.

## Caitlyn Clark – National Renewable Energy Laboratory

Dr. Caitlyn Clark is a renewable energy researcher and engineer focused on incorporating risk, reliability, and resilience into NREL's suite of renewable energy design, modeling, and analysis tools. She is a key contributor to hybrid power plants, offshore wind systems, distributed systems, green hydrogen production, and wind workforce strategy, modeling, and demonstration, as well as to three software products. She is an active member in international standards development in these subjects. Her projects span NREL's research centers and necessitate frequent collaboration with teams across other national labs, and external industrial and research institution partners. Her work commonly includes business development, including developing relationships and agreements with industry partners, convening and coordinating industry stakeholder groups, and actively aligning research with industry challenges. She graduated with a degree in ecological engineering at Oregon State University in 2014, and a Ph.D. in mechanical engineering in 2019.

## Bai Cui – National Renewable Energy Laboratory



Dr. Bai Cui is a researcher in the energy systems control and optimization group at NREL. He received his Ph.D. degree in electrical and computer engineering from Georgia Tech in 2018. Prior to joining NREL in 2019, he was a postdoctoral appointee at Argonne National Laboratory. Cui's general research interests are in the application of optimization and control techniques in power system analysis. Topics of recent interest include integration of distributed energy resources, power system resilience, and power system steady-state analysis.

## Bing Dong – Syracuse University

Dr. Bing Dong is an associate professor in the mechanical and aerospace engineering department at Syracuse University. He also serves as associate director of the Syracuse Center of Excellence for Environmental and Energy Systems. Dong's research interests include building energy efficiency, occupant behavior modeling at both building and urban scales, buildings-to-grid integration, building controls and diagnostics, and big data analytics. Dong received his Ph.D. from Carnegie Mellon University.

## Michael (Misha) Chertkov – University of Arizona

Dr. Michael (Misha) Chertkov is a professor of mathematics and chair of the Graduate Interdisciplinary Program (GIDP) in applied mathematics, member of GIDP in statistics and data science, and (affiliate) professor of computer science at the University of Arizona. His area of focus at the University of Arizona is integration of data science disciplines (e.g., machine learning and AI) into applied mathematics to resolve challenges in natural sciences and engineering. Chertkov received his Ph.D. in physics from the Weizmann Institute of Science in 1996, spent 3 years at Princeton University as an R.H. Dicke fellow in the Physics Department, and joined Los Alamos National Laboratory (LANL) in 1999, initially as a J.R. Oppenheimer fellow and then as a technical staff member. During his 20 years at LANL he led multiple DOE and Defense Threat Reduction Agency projects, in particular on "physics of algorithms," "optimization, inference and learning of energy systems," and "machine learning for turbulence." Chertkov moved to Tucson in 2019. He has published more than 250 papers and is a fellow of the American Physical Society and a senior member of IEEE.

## Emiliano Dall'Anese – University of Colorado–Boulder

Dr. Emiliano Dall'Anese is an assistant professor in the department of electrical, computer, and energy engineering at the University of Colorado–Boulder, and an affiliate faculty member of the department of applied mathematics. He received his Ph.D. in information engineering from the University of Padova, Italy, in 2011. He was a postdoctoral associate at the University of Minnesota from 2011 to 2014. He started his appointment as an assistant professor at the University of Colorado–Boulder in 2018. His background is in the broad areas of optimization theory, learning, and control. The objective of his current research efforts is to advance theory, algorithms, and analysis for decision systems. The current focus is on online optimization and data-enabled optimization of network and dynamical systems. Application domains include power systems and healthcare.

## Paritosh Das – National Renewable Energy Laboratory

Paritosh Das is a research engineer in the Accelerated Deployment and Decision Support Center at NREL. His research interests include capacity expansion modeling with a focus on adoption of distributed energy resources, risk and decision-making, and customer behavior. He is also the technical lead for NREL's open-source Distributed Generation Market Demand Model, or dGen™, an agent-based model to forecast distributed energy resource deployment.

## Daniel Eisenberg – Naval Postgraduate School

Dr. Daniel Eisenberg is an assistant professor of operations research at the Naval Postgraduate School (NPS) and deputy director of the NPS Center for Infrastructure Defense. Eisenberg's research focuses on the design, operation, and adaptation of resilient infrastructure systems with emphasis on applying resilience engineering theory to improve system design and emergency operations. He uses tools from operations research, engineering, and public administration to link built and social systems together and identify fragilities in existing practices. He currently leads projects on the design and management of resilient island and military installation infrastructure systems in the U.S. Virgin Islands, Rhode Island, and Hawaii. Eisenberg is also an educator and helps advance critical infrastructure knowledge worldwide through in-residence classes at NPS and the delivery of NATO short courses across Europe and the Middle East.

## Johney Green, Jr. – National Renewable Energy Laboratory

Dr. Johney Green, Jr. serves as the associate laboratory director for mechanical and thermal engineering sciences at NREL. He oversees NREL's transportation, buildings, wind, water, geothermal, advanced manufacturing, concentrating solar power, and Arctic research programs, which encompass a portfolio of more than $200 million and more than 550 employees. The directorate conducts research and development to enable technology innovations in the areas of energy efficiency, sustainable transportation, and renewable power. Additionally, Green transformed NREL's wind site into the Flatirons Campus and transitioned the campus from a single-program wind research site to a multiprogram research campus that is the foundational experimental platform for the U.S. Department of Energy's Advanced Research on Integrated Energy Systems initiative.

## Carishma Gokhale-Welch – National Renewable Energy Laboratory

Carishma Gokhale-Welch is a project lead at NREL. With nearly two decades of domestic and international experience, her work focuses on clean energy planning and strategy in the United States and in emerging markets. Gokhale-Welch leads complex, multi-stakeholder technical teams that provide place-based technical assistance to support communities with energy transitions, as well as power sector transformation activities in Asia and North Africa. Before coming to NREL, her work involved overseeing activities ranging from strategic planning, building partnerships and new initiatives, to mine reclamation and watershed management. Raised in India, she was educated at the University of Mumbai and at Yale University, where she earned a master's degree in environmental management and a certificate in financing and deploying clean energy.

## Emily Grubert – University of Notre Dame

Dr. Emily Grubert a civil engineer and environmental sociologist currently serving as an associate professor at the University of Notre Dame, working on enacting a just energy transition by researching ways to make decision-making more just, effective, and informed. Specifically, Grubert studies decarbonization and how community and societal priorities can be better incorporated into multicriteria policy and project decisions, mainly related to energy, water, and infrastructure systems. Grubert is particularly interested in understanding how infrastructure decisions can be used to embed and enact structural justice. She completed her Ph.D. in environment and resources at Stanford University in 2017.

## Majeed M. Hayat – Marquette University

Dr. Majeed M. Hayat received M.S. and Ph.D. degrees in electrical and computer engineering from the University of Wisconsin–Madison in Madison, Wisconsin in 1988 and 1992, respectively. He is currently a professor and department chair of electrical and computer engineering with Marquette University in Milwaukee, Wisconsin. He has authored or coauthored more than 110 peer-reviewed journal articles and 135 conference papers with nearly 6,200 citations (H-Index: 40), and has 14 issued patents, six of which have been licensed. His research interests include a broad range of topics including resilience and reliability of interdependent cyber-physical systems, dynamical modeling of cascading phenomena with applications to power systems, avalanche photodiodes, statistical communication theory, image processing for infrared focal-plane-arrays, algorithms for spectral and radar sensing and imaging, optical communication, and performance modeling of high-performance computing systems. From 2004 to 2010, he was an associate editor for the Optics Express (photodetectors and image processing), and an associate editor and a member of the conference editorial board for the IEEE Control Systems Society. From 2010 to 2013, he was the chair of the topical committee on photodetectors, sensors, systems, and imaging of the IEEE Photonics Society. From 2014 to 2018, he was an associate editor for the IEEE Transactions on Parallel and Distributed Systems. In 1998, he was the recipient of the National Science Foundation Early Faculty Career Award. Hayat is a fellow of IEEE, International Society for Optical Engineering, Optica, and Optical Society of America.

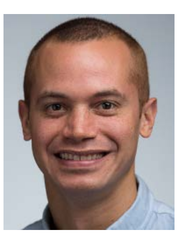
## Patricia Hidalgo-Gonzalez – University of California–San Diego

Dr. Patricia Hidalgo-Gonzalez is an assistant professor at the University of California (UC)–San Diego. She is a National Science Foundation Graduate Research Fellowships Program fellow, Siebel Scholar in Energy, Rising Star in Electrical Engineering and Computer Science, and has been awarded Best Paper at the Power Systems Computation Conference 2020, the UC–Berkeley Graduate Opportunity Program Award, and the Outstanding Graduate Student Instructor Award. At UC–San Diego, she directs the Renewable Energy and Advanced Mathematics (REAM) lab which focuses on high penetration of renewable energy using optimization, control theory, and machine learning. Hidalgo-Gonzalez co-developed a stochastic power system expansion model to study western North America's grid under climate change uncertainty. She is currently working with the California Energy Commission to understand the value and role of long-duration energy storage. She is also supported by the U.S. Department of Energy to study the value of wave energy and offshore wind for the U.S. power grid. In addition to capacity expansion modeling, she works on power dynamics with low and variable inertia, and controller design using machine learning and safety guarantees. She is generally interested in power dynamics, electricity market redesign to aid the integration of renewable energy, microgrids for wildfire risk mitigation, distributed control, and learning for dynamical systems with safety guarantees. Hidalgo-Gonzalez is part of the IEEE Power & Energy Society Task Force titled "Data-Driven Controls for Distributed Systems." She holds a M.S. and a Ph.D. from UC–Berkeley.

## Wan-Lin Hu – SLAC National Accelerator Laboratory

Dr. Wan-Lin Hu is an associate staff scientist in the Grid Integration and Mobility (GISMo) group at SLAC National Accelerator Laboratory, operated by Stanford University. Before joining SLAC, she was a postdoctoral scholar at Stanford University. Hu received a doctorate in mechanical engineering at Purdue University with a focus in human-centered design and human factors engineering. With extensive experience in engineering design, human-machine interactions, and human subject research, her current research focus is human-in-the-loop model development and the user interface and workflow improvement for human-in-the- loop complex systems.

## Eric Lockhart – National Renewable Energy Laboratory



Eric Lockhart leads the integrated decision support group at NREL. He and his team lead complex energy projects and programs that require strategy development, analytics, and technical decision-making. Eric is also the principal investigator for the Solar Energy Innovation Network (SEIN), which is a project focused on novel applications of solar and storage in domestic settings. His work through SEIN includes projects focused on resilience benefits that micro-grids can provide and potential synergies between distributed solar and electric vehicle charging. In addition, he leads off-grid micro-grid research and technical assistance efforts focused on Sub-Saharan Africa, with topics including approaches to system design, community agreements, and pathways to developing sustainable business models.

## Enrique Mallada – John Hopkins University

Dr. Enrique Mallada has been an associate professor of electrical and computer engineering at Johns Hopkins University since 2022. Before joining Hopkins in 2016 as an assistant professor, he was a post-doctoral fellow at the Center for the Mathematics of Information at the California Institute of Technology from 2014 to 2016. He received his telecommunications engineering degree from Universidad ORT Uruguay in 2005 and his Ph.D. degree in electrical and computer engineering with a minor in applied mathematics from Cornell University in 2014. Mallada was awarded the Johns Hopkins Alumni Association Excellence in Teaching Award in 2021, the National Science Foundation Faculty Early Career Development Program (CAREER) Award in 2018, the Electrical and Computer Engineering Director's Ph.D. Thesis Research Award for his dissertation in 2014, the Cornell University's Jacobs Fellowship in 2011, and the Organization of American States scholarship from 2008 to 2010. His research interests lie in the areas of control, networked dynamics, and optimization, with applications to engineering networks such as power systems and the internet.

## Jeffrey Marqusee – National Renewable Energy Laboratory

Dr. Jeffrey Marqusee is a senior research advisor at NREL where he serves as senior advisor for NREL's energy systems integration directorate. At NREL he provides strategic guidance for NREL's national security work, advises the U.S. Department of Defense's (DoD's) energy technology programs, and conducts research on energy resilience, microgrids, and energy storage. He also is an independent consultant on energy, climate, and resiliency issues. Prior to joining NREL he served as a chief scientist at Noblis, a nonprofit science, technology, and strategy organization. He has over 20 years of government leadership in research, technology development, and policy aimed at making the DoD a more sustainable and effective organization. At DoD he served as the executive director of the Strategic Environmental Research and Development Program and the Environmental Security Technology Certification Program. He led the DoD's science and technology investments in energy and environment. Before joining DoD, he worked at the Institute for Defense Analyses, Stanford University, the University of California, and the National Institute of Standards and Technology. He has a Ph.D. from the Massachusetts Institute of Technology.

## Line Roald – University of Wisconsin–Madison

Dr. Line Roald is an assistant professor and Grainger Institute fellow in the department of electrical and computer engineering at the University of Wisconsin–Madison. She received her Ph.D. degree in electrical engineering (2016) from ETH Zurich, Switzerland and was a postdoctoral research fellow with the Center of Non-Linear Studies at Los Alamos National Laboratory. She is a recipient of the National Science Foundation CAREER Award and the University of Wisconsin–Madison Electrical and Computer Engineering Outstanding Graduate Mentor Award. Her research interests center around modeling and optimization of the electric grid, with a particular focus on risk management, uncertainty modeling, and climate change mitigation and adaptation.

## Jeffrey Schlegelmilch – Columbia University

Jeff Schlegelmilch is a research scholar and the director of the National Center for Disaster Preparedness, Columbia Climate School, at Columbia University. He is also an executive advisor at Quanta Technology. His areas of expertise include public health preparedness, community resilience, and the integration of private and public sector capabilities. Prior to his work at Columbia, he was the manager for the international and non-healthcare business sector for the Yale New Haven Health System Center for Emergency Preparedness and Disaster Response. He was also previously an epidemiologist and emergency planner for the Boston Public Health Commission. He is also the author of “Rethinking Readiness: A brief guide to twenty-first-century megadisasters” published by Columbia University Press.

## Benjamin K. Sovacool – University of Sussex

Dr. Benjamin K. Sovacool is a professor of energy policy at the Science Policy Research Unit (SPRU) at the University of Sussex Business School in the United Kingdom. He works as a researcher and consultant on issues pertaining to global energy policy and politics, energy security, energy justice, climate change mitigation, and climate change adaptation. More specifically, his research focuses on renewable energy and energy efficiency, the politics of large-scale energy infrastructure, designing public policy to improve energy security and access to electricity, the ethics of energy, and building adaptive capacity to the consequences of climate change.

## Deepthi Vaidhynathan – University of Colorado–Boulder

Deepthi Vaidhynathan received an M.S. degree in electrical engineering from the University of Colorado–Boulder in 2015. She is a senior research engineer with the Computational Science Center at the National Renewable Energy Laboratory in Golden, Colorado. Her interests are in energy system integration, grid modeling and simulation, performance optimization for scientific software.

## Parth Vaihnav – University of Michigan

Parth Vaihnav is an assistant professor at the School for Environment and Sustainability at the University of Michigan. His work aims to understand how technology can help solve social problems. Much of his research addresses the environmental and human health consequences of energy production and use. Vaihnav employs quantitative decision analysis, buttressed by qualitative insight, to understand how economic, political, and operational realities constrain technology deployment. This research focuses on finding strategies to decarbonize the economy, and to adapt to the warming that has occurred and will occur even if we cut greenhouse gas emissions very rapidly. He is keenly interested in finding ways to make both mitigation and adaptation equitable.

## Adam Warren – National Renewable Energy Laboratory

Dr. Adam Warren is the director of the Accelerated Deployment and Decision Support (ADDS) Center within the energy systems integration directorate at NREL. ADDS focuses on the later stages of research, development, demonstration, and deployment. His team addresses the technical, policy, and financial hurdles to developing resilient, advanced energy technologies at scale. The center supports government agencies, utilities, communities, and corporations to meet ambitious clean energy goals while informing the lab's research and analysis efforts. Warren is the co-director of the Advanced Energy System graduate program at the Colorado School of Mines. This program is a collaborative effort between the university and NREL.

# Appendix B – Workshop Agenda and Abstracts

## *Workshop Agenda*

**Human Dimensions of Energy Systems**
NREL Workshop, Golden, Colorado
September 6–7, 2022

Tuesday, September 6

***Introductions***

8:15 – 8:30 Arrive at NREL and Check in

8:30 – 8:45 Welcome and Workshop Charge
**Johney Green and Adam Warren, NREL**

***Understanding, Modeling and Simulation of Human Behavior in Energy Systems***

8:45 – 9:20 *Building Energy Resilience: Dynamics at the intersection of infrastructure and broader civil society*
**Jeffrey Schlegelmilch, Columbia University**

9:20 – 9:55 *Understanding Occupant Behavior: from Smart Buildings to Cities*
**Bing Dong, Syracuse University**

9:55 – 10:30 *Resilience and Surprise in Energy Infrastructure Systems*
**Daniel Eisenberg, Naval Postgraduate School**

10:30 – 10:45 Break

10:45 – 11:20 *A Stochastic Model for Cascading Failures in Power Grids in the Presence of Operator Errors*
**Majeed Hayat, Marquette University**

11:20 – 11:45 *Incorporating Human Behavior and Distributed Control for Grid Resilience*
**Deepthi Vaidhynathan and Caitlin Clark, NREL**

11:45 – 12:05 Discussion

12:05 – 13:05 Discussion and Working Lunch

13:05 – 13:30 *Technology Adoption and Consumer Behavior*
**Paritosh Das, NREL**

***Community Energy Transitions and Justice***

13:30 – 13:55 *NREL's Energy Justice and Place-Based Efforts*
**Eric Lockhart and Carishma Gokhale-Welch, NREL**

13:55 – 14:30 *Exploring the Human Networks, Lived Experiences and Qualitative Methods for Decarbonization*
**Benjamin Sovacool, University of Sussex**

14:30 – 14:45 Break

14:45 – 15:20 *Equity, Behavior, and Electrification: Case Studies from the Residential and Power Sectors*
**Parth Vaishnav, University of Michigan**

15:20 – 15:55 *Community-Focused Decision-Making*
**Emily Grubert, University of Notre Dame**

15:55 – 16:55 Discussion and closing remarks

18:00 – 19:00 Optional dinner at Sherpa House

Wednesday, September 7

8:15 – 8:30 Arrive at NREL and Check in

8:30 – 8:45 Workshop and Introduction to Day Two
**Jeff Marqusee, NREL**

***Modeling of Human Behavior in Optimization and Control***

8:45 – 9:20 *Decentralized Optimal Power Flow for Time-Varying Network Topologies Using Machine Learning*
**Patricia Hidalgo-Gonzalez, UC–San Diego**

9:20 – 9:55 *Collective Decision vs Comfort of Customers: Statistical Mechanics of Thermostatically Controlled Multi-Zone Buildings*
**Michael (Misha) Chertkov, University of Arizona**

9:55 – 10:30 *Towards an Equitable and Personalized Energy Management via Learning-Based Online Optimization*
**Emiliano Dall'Anese, CU–Boulder**

10:30 – 10:45 Break

10:45 – 11:10 *Distribution System Voltage Control with Random Customer Participation*
**Bai Cui and Guido Cavraro, NREL**

11:10 – 11:45 *Unintended Consequences of Market Designs: The Role of Inelastic Demand in Two-Stage Electricity Markets*
**Enrique Mallada, Johns Hopkins University**

11:45 – 12:20 *New Challenges for Power Systems Optimization: Capturing the Environmental and Social Context of the Electric Grid*
**Line Roald, University of Wisconsin–Madison**

12:20 – 13:20 Discussion and Working Lunch

13:20 – 13:55 *Assessing Human Reliability with a Critical Group: Transmission Line Operators*
**Joana Abreu, TRC**

***People in the Loop Modeling and Analysis***

13:55 – 14:30 *Human-in-the-Loop Modeling to Enhance Operational Efficiency*
**Wan-Lin Hu, SLAC**

14:30 – 14:45 Break

14:45 – 15:10 *Human in the Energy Loop*
**Doug Arent, NREL**

15:10 – 15:45 *Operator-in-the-Loop and Virtual Operator Studies for Nuclear Power Plants*
**Ronald L. Boring, INL**

15:45 – 16:45 Discussion and Closing Remarks

# Abstracts

## Understanding, Modeling, and Simulation of Human Behavior in Energy Systems

### *Building Energy Resilience: Dynamics at the Intersection of Infrastructure – Jeffrey Schlegelmilch, Columbia University*

Grid disruptions as a result of disasters are increasing, highlighting the complex interplay between engineering and human systems. As our reliance on electricity increases in a more electrified world, the functioning of the grid is increasingly what emergency managers refer to as a “community lifeline,” or an enabling factor for the broader functioning of society. This requires looking at resilience through a broader lens that takes into account the cascading impacts that grid dynamics have in facilitating resilience amid different types of societal vulnerabilities. This presentation provides an overview of this intersection of grid disruptions and broader societal impacts, and how grid investments can benefit broader community resilience.

### *Understanding Occupant Behavior: from Smart Buildings to Cities – Bing Dong, Syracuse University*

By 2050, a staggering 70% of the world’s population is projected to live and work in cities, while two-thirds of global primary energy consumption will be attributed to cities, leading to the production of 71% of global direct energy-related greenhouse gas emissions. People currently spend more than 90% of their time in buildings, which contributes to more than 70% of overall U.S. electricity usage. Considering this, occupant behavior becomes one of the leading influences on energy consumption in buildings and cities. The proliferation of urban sensing, Internet of Things, and big data in cities provides unprecedented opportunities for a deeper understanding of occupant behavior patterns at both building and urban scales. Meanwhile, traditional design and operation of the smart building ecosystem only considers physical aspects of energy infrastructure. Future smart cities, with connected buildings, increasing penetration of distributed energy resources (DERs), and widely adopted electric vehicles, require an occupant-centric approach for optimal and distributed coordination of clusters of buildings and DERs with the smart grid while considering human behavior and mobility. This talk will present and discuss how occupant behavior impacts building operations while considering grid needs and flexibility, with an emphasis on efforts to model occupant behavior at both building and urban levels, and improve buildings-to-grid integration across spatial scales in cities, to foster an occupant-centric ecosystem for future smart cities.

### *Resilience and Surprise in Energy Infrastructure Systems – Daniel Eisenberg, Naval Postgraduate School*

Resilience analysis of critical infrastructure systems tends to focus on measuring the capacity of the system to withstand and rebound its function after a disruption. Resulting metrics and measures rely on the critical functionality curve (CFC) which approximates resilience as the loss and recovery process relative to a known functional baseline. However, this perspective on resilience assumes decision-makers (e.g., system operators, emergency managers) had perfect information about system state and function as failures occur. In practice, individuals managing infrastructure failures may have poor understanding of system state and function that leads to decisions that exacerbate failures and prolong recovery efforts. In this presentation, we define a new way to use the CFC to study surprise— i.e., an event that reveals when current understanding of emergency response needs does not match expectations—by refocusing the curve on assessing decision maker beliefs about system state, rather than assuming perfect knowledge. Through this new method, we can identify different types of surprise and their implications for emergency response. We show the implications of this approach given recent disasters that impacted the Oroville dam and Marine Corps Base Camp Lejeune. We conclude with some recent efforts to develop simulation games to train systems modelers and military personnel how to manage surprise given a fictitious fuel network.

### *A Stochastic Model for Cascading Failures in Power Grids in the Presence of Operator Errors – Majeed Hayat, Marquette University*

Despite the rapid increase in the automation of monitoring and control of modern power grids, human operators continue to play a crucial role in the reliable operation of the grid. However, the operators' actions can be non-optimal due to various factors affecting their performance, which are dependent on both the operators' conditions and the nature of the decisions and actions to be made. Here, we review an analytic model, based on Markov chains, for predicting the dynamics of cascading failures in power grids, following initial transmission-line failures, while capturing the effects of operators' behavior, as quantified by the probability of human error under various circumstances.

### *Incorporating Human Behavior and Distributed Control for Grid Resilience – Deepthi Vaidhynathan and Caitlyn Clark, NREL*

Power grids are undergoing a fundamental transition, with traditionally passive consumers increasingly managing their energy consumption, production, and storage through distributed energy resources (DERs). As we transition to this new paradigm, complexities driving energy demand and grid stability, including human behavior, have yet to be fully included in power flow and grid control models. Agent-based modeling (ABM) is a modeling approach that provides the ability to represent individual energy consumer behavior across a heterogenous population to observe emergent system behavior. In our work, we develop an ABM to incorporate human behavior and social interactions into grid control and power flow modeling. This tool enables us to explore: 1) how human behavior affects grid stability during disturbance events (or perceived disturbance events), 2) how various control strategies perform under the increasing influence of human behavior, and 3) how community composition and access to DERs affect human behavior and grid resilience during disturbance events. Results indicate significant changes in grid control when human behavior is included in power flow simulations. The impact of human behavior increases with increasing levels of DERs on the grid. Resilience events, such as low PV solar generation, also intensify grid stability issues, however, advanced control methods enable stability during these events. Including human behavior in power flow modeling is critical to ensuring robust control development, particularly as DER penetration continues to increase and the U.S. electric grid becomes more dependent on distributed, renewable grid systems.

### *Technology Adoption and Consumer Behavior – Paritosh Das, NREL*

Forecasting the adoption and operation of distributed energy resources, e.g., rooftop PV, behind-the-meter battery storage, etc., at fine spatial resolutions is an integral part of distribution system planning and integrated resource planning. Behavioral research has shown that consumers don't always act rationally as generally considered within various techno-economical modeling frameworks. Accurately understanding and incorporating consumer behavior will help in the better design of policies, incentives, and programs in order to incentivize technology adoption over time and geography.

## Community Energy Transitions and Justice

### *NREL's Energy Justice and Place-Based Efforts – Eric Lockhart and Carishma Gokhale-Welch, NREL*

Carishma Gokhale-Welch and Eric Lockhart discuss NREL's energy justice strategy and highlight place-based efforts that support that vision. NREL's energy justice strategy seeks to drive equitable access to, participation in, and distribution of the benefits of affordable, sustainable, reliable, and resilient energy to enable a clean energy future for the world while also remediating social, economic, and health burdens of those historically harmed by the energy system. There are many NREL projects and activities that support that vision, but this discussion will highlight two of those projects: Communities Local Energy Action Program (C-LEAP) and the Solar Energy Innovation Network (SEIN), which both focus on supporting underserved or fossil-transitioning communities.

### *Exploring the Human Networks, Lived Experiences and Qualitative Methods for Decarbonization*

### *– Benjamin Sovacool, University of Sussex*

This presentation explores three different dimensions of the human networks of energy technology and behavior. It summarizes insights from recent Living Labs research in the United Kingdom, as well as the salience of lived experiences and naturalistic observation research. All are very useful at depicting revealed preferences rather than stated preferences. The presentation also touches upon empirical research on control, privacy, gender, and violence.

### *Equity, Behavior, and Electrification: Case Studies from the Residential and Power Sectors*

### *– Parth Vaishnav, University of Michigan*

In this talk, I present three case studies where insight into human behavior might constrain technology choice, policy, or operation in energy systems. First, I discuss an experiment to disentangle public opposition due to the dread of nuclear power from opposition stemming from its actuarial risk. Respondents were asked to build a power generation portfolio that cuts carbon dioxide emissions, given information about the actuarial risks of technologies. Half the sample is exposed to the nuclear power label while the other half is treated with the risk information but blinded to the label. Respondents who saw the labels deployed 6.6 percentage points less nuclear power as a share of the U.S. electricity mix. Second, I report on an analysis that leverages smart thermostat data to assess the effect of customer override on the reliability contribution of demand response programs. The preliminary results from this analysis suggest that overrides reduced the reliability contribution of the program from 34% to 31%, or 12% to 9% if the sample was scaled to represent the 7.5 million single-family homes in California. Overrides led to a 50% reduction in cooling load savings, with override impacts increasing with demand response event duration. Third, I report on the early results of an effort to gather primary data about energy use in low-income families in Washtenaw and Wayne counties in Michigan. I will discuss the environmental justice implications of electrifying heating for these homes, the effect of time of use pricing, and the differential impact of home retrofit costs.

### *Community-Focused Decision-Making – Emily Grubert, University of Notre Dame*

Planned transition, conscious of existing conditions and community needs, is crucial for successful decarbonization.  Decarbonization is two things: industrialization and deindustrialization. We talk a lot about the benefits of industrialization. We talk a lot about the benefits of decarbonization. We talk much less about the disbenefits of industrialization, anything about deindustrialization, and how we manage the mid-transition. How do we facilitate a just transition away from fossil fuels?

## Modeling of Human Behavior in Optimization and Control

### *Decentralized Optimal Power Flow for Time-Varying Network Topologies Using Machine Learning – Patricia Hidalgo-Gonzalez, UC–San Diego*

Distributed energy resources (DERs) have been continuously increasing in recent years. When DERs are uncontrolled, technical operating challenges can arise such as over-voltage and congestion. Therefore, Distribution System Operators (DSO) would benefit from mitigating these difficulties by controlling reference set points for local PV inverters and batteries. Furthermore, as the deployment of new control agents (DERs) takes place in the distribution network, a new question arises on how to manage these agents given the time-varying environment (new nodes and branches in the graph). This work addresses this gap by proposing a machine learning framework to design controllers that are robust to topological changes for each new (and existing) inverter-connected DER. The adoption of DERs has been inequitable across income and race in California. This raises fundamental questions about how technology and policy transition pathways can ensure that benefits are distributed fairly, and costs are not disproportionately borne by low-income and minority (LIM) communities. The last portion of the talk discusses planned collaborative interdisciplinary work on how this machine learning framework and other methods (with varying degrees of information required among DERs in a network and equity metrics) will be applied to three LIM communities in California. Finally, we provide an overview of DERConnect at UC–San Diego, the first grid-connected, customizable, and dedicated power system with all the required components and DER types for large-scale distributed control. By 2025, there will be national real-time remote access to implement and validate algorithms for human-in-the-loop DERs management.

### *Collective Decision vs Comfort of Customers: Statistical Mechanics of Thermostatically Controlled Multi-Zone Buildings*
### *– Michael (Misha) Chertkov, University of Arizona*

We study the collective, statistical phenomena and constraints associated with the aggregation of individual cooling units from a statistical mechanics perspective. These units are modelled as Thermostatically Controlled Loads (TCLs) and represent zones in a large commercial or residential building. Their energy input is centralized and controlled by a collective unit – the Air Handling Unit (AHU) — delivering cool air to all TCLs, thereby coupling them together. Aiming to identify representative qualitative features of the AHU-to-TCL coupling, we build a realistic but also sufficiently simple model and analyze it in two distinct regimes: the Constant Supply Temperature (CST) and the Constant Power Input (CPI) regimes. In both cases, we center our analysis on the relaxation dynamics of an individual TCL temperature to a steady state following a demand response (DR) request. We observe that while the dynamics are relatively fast in the CST regime, resulting in all TCLs evolving around the control setpoint, the CPI regime reveals the emergence of bi-modal probability distribution and two, possibly strongly separated, time scales. This observation, new and to the best of our knowledge overlooked in the context of the multi-zone energy building engineering, is related to what is known as Kramer's phenomenon. We observe that the two modes of the CPI regime are associated with all TCLs being in low-flow (below temperature set point) and high-flow (above temperature set point) states, respectively. Dynamics of an individual TCL is governed by a competition of under-damped relaxation in a double-well potential (with two minima corresponding to the two modes) and stochastic fluctuations. These observations have direct implications on the operations of centralized cooling systems in buildings. They indicate that a balance needs to be struck between occupational comfort—related to variations in the individual temperatures—and power output predictability—the main focus of the DR schemes.

### *Towards an Equitable and Personalized Energy Management via Learning-Based Online Optimization*
### *– Emiliano Dall'Anese, CU– Boulder*

Optimization problems associated with a variety of tasks in power systems—such as demand response, building control, optimal power flow, etc. —typically include cost functions associated with the system performance as well as the (dis)comfort, (dis)satisfaction, and safety of users owning assets of interacting with the system. The latter is typically captured through synthetic cost models that rely on large-scale statistics or just conventional wisdom. Since similar cost models are applied to all users, traditional setups fail in capturing the diversity in the perception of (dis)comfort, (dis)satisfaction, and safety of individual users, and hardly encapsulate equity and fairness measures. This talk takes a departure from this classical view and explains how principled optimization algorithms can be augmented with supervised learning methods to learn the cost function associated with each user based on the users' experience and feedback. We present an online optimization framework with concurrent learning, where the cost functions are learned on-the-fly based on the users' feedback on their perceived (dis)comfort, (dis)satisfaction, and safety, as well as feedback on their perception of equity and fairness. The talk will discuss how to combine monotone operator theory, statistical learning, and optimization to answer key technical questions pertaining to transient behavior and performance of the proposed schemes.

### *Distribution System Voltage Control with Random Customer Participation – Bai Cui, NREL*

With the increased observability and controllability of distribution systems, the share of behind-the-meter systems is trending upwards rapidly. As a consequence, the impact of human behaviors on system performance can no longer be ignored and should be reflected in energy management system models. In this talk, we discuss the problem of distribution system voltage control by load curtailment where the customer compliance of the load curtailment signal is random. We discuss the modeling of the optimal voltage control problem with random customer compliance as a chance constrained optimization problem, its tractable safe approximation using second-order cone programming, and a scenario-based mixed-integer reformulation as well as the associated solution method based on augmented Lagrangian decomposition.

### *Unintended Consequences of Market Designs: The Role of Inelastic Demand in Two-Stage Electricity Markets – Enrique Mallada, Johns Hopkins University*

In this talk, we seek to highlight the importance of accounting for the incentives of all market participants when designing market mechanisms for electricity. To this end, we perform a Nash equilibrium analysis of two different market mechanisms that aim to illustrate the critical role that the incentives of consumers and other new types of participants, such as storage, play in the equilibrium outcome. Firstly, we study the incentives of heterogeneous participants (generators and consumers) in a two-stage settlement market, where generators participate using a supply function bid and consumers use a quantity bid. We show that strategic consumers are able to exploit generators' strategic behavior to maintain a systematic difference between the forward and spot prices, with the latter being higher. Notably, such a strategy does bring down consumer payments and undermines the supply-side market power. We further observe situations where generators lose profit by behaving strategically, a sign of overturn of the conventional supply-side market power. Secondly, we study a market mechanism for multi-interval electricity markets with generator and storage participants. Drawing ideas from supply function bidding, we introduce a novel bid structure for storage participation that allows storage units to communicate their cost to the market using energy cycling functions that map prices to cycle depths. The resulting market-clearing process—implemented via convex programming—yields corresponding schedules and payments based on traditional energy prices for power supply and per-cycle prices for storage utilization. Our solution shows several advantages over the standard prosumer-based approach that prices energy per slot. In particular, it does not require a priori estimation of future prices and leads to an efficient, competitive equilibrium.

### *New Challenges for Power Systems Optimization: Capturing the Environmental and Social Context of the Electric Grid*
### *– Line Roald, University of Wisconsin–Madison*

As climate change unfolds, the electric grid will experience more frequent extreme weather impacts, including heightened wildfire risk, more widespread and intense heatwaves, and more frequent hurricanes, flooding, or tornadoes. Under these circumstances, it may not always be possible to maintain electric service to all customers. Optimally operating electric systems under these circumstances requires not only an electrical model of the grid, but also methods to reflect the social and environmental context around the grid. Understanding both the environment around the power lines and how communities cope in outage scenarios is critical to answer questions such as "How can we effectively mitigate both wildfire risk and the impact of power outages?" or "When optimizing the system restoration process after a disaster, how do we account for the presence of customer-owned distributed energy resources?" In this talk, we discuss our recent work on modeling and optimization in these two examples. We also reflect on how the choice of input data, objectives and constraints can have significant impact on the outcomes for both the overall system and individual customers.

### *Assessing Human Reliability with a Critical Group: Transmission Line Operators*
### *– Joana Abreu, TRC*

The propagation of events that cause blackouts is non-linear, accelerating with time. While stochastic simulation has been used to model cascading events, the effects of the human operator's understanding of the de-energizing of power lines in real-time complicate this estimation. The compounding effects of operator error, and other performance shaping factors, can change outcomes at any given time. Presented as a model incorporating the probability of human error under different scenarios, the presentation will discuss research to assign a human reliability probability to discrete data obtained from grid operator interviews analyzing power restoration activities.

## People in the Loop Modeling and Analysis

### *Human-in-the-Loop Modeling to Enhance Operational Efficiency*
### *– Wan-Lin Hu, SLAC*

Humans are intimately "in the loop" in almost all of our most important and complex control systems, such as power grids and large-scale scientific instruments. Even where automation is beginning to outperform human operators on some tasks, a smooth combination of human and automated control is almost always required to handle unusual situations. To maximize the benefits of these capabilities, the complexity introduced by the relationships and dependencies between the human and non-human components of the system needs to be managed. In this talk, along with a simple computer-based operator workstation and observations conducted at Linac Coherent Light Source (LCLS) control rooms, we will discuss two approaches to enhancing operational efficiency with human-in-the-loop modeling: to improve operator training and improve system design.

### *Human in the Energy Loop – Doug Arent, NREL*

This brief presentation will summarize 3 years of focused research conducted at NREL on "Human in the Energy Loop," including advanced work on real-time informing of consumer preferences, individual comfort perception and experimentation, and multidimensional analysis of mobility mode choice. We discuss operational efficiency with human-in-the-loop modeling to improve operator training and improve system design.

### *Operator-in-the-Loop and Virtual Operator Studies for Nuclear Power Plants – Ronald L. Boring, INL*

Idaho National Laboratory's Human Factors and Reliability Department has conducted significant research on operations for nuclear power generation. The Human Systems Simulation Laboratory serves as a design and evaluation facility for control room modernization of existing nuclear power plants and for concepts of operation for advanced reactors like microreactors and small modular reactors. INL staff, working with reactor vendors and utilities, use this facility to develop prototype digital and automated control rooms. An important element of the facility is its use to evaluate human performance, to ensure the suitability of the human-machine interfaces for licensing and subsequent commercial use. Human performance data are also used to build operator models (i.e., virtual operators or so-called digital human twins) based on human reliability analysis methods. The purpose of these operator models is to capture risk such as human error traps resulting from new modes of operation and novel user interfaces. Nuclear power plants, which constitute about 20% of U.S. electricity generation, offer a useful test bed for studying the human dimensions of energy generation.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