US-European Workshop

GRID AT THE EDGE: TOWARDS THE ZERO-CARBON POWER GRID WITH IMPROVED VISIBILITY, SAFETY, AND RELIABILITY

Location: Split, Croatia

Date: May 23-24, 2022

Final Report

Authors

Mladen Kezunovic, Workshop Co-Chair

Christian Rehtanz, Workshop Co-Chair

Workshop Discussion Record Consolidation Team

Topic #1: Payman Dehghanian, George Washington University

Topic #2: Mads Almassalkhi, University of Vermont

Topic #3: Anurag Srivastava, West Virginia University

Topic #4: Meng Wu, Arizona State University

Workshop Discussion Record Keeping Team

Richard Zhang, University of Illinois-Urbana Champaign

Hao Zhu, The University of Texas-Austin

Junbo Zhao, University of Connecticut

Bolun Hu, Columbia University

Jianhua Zhang, Clarkson University

Quanyan Zhu, NY University

Chiara Lo Prete, The Pennsylvania State University

Timothy Hansen, South Dakota State University

August 8, 2022

Executive Summary

This report summarizes discussions and recommendations from the NSF-sponsored Joint US-European Workshop titled "Grid at the Edge: towards the zero-carbon power grid with improved visibility, safety and reliability" held in Split, Croatia on May 23-24, 2022. The workshop was attended by over 70 participants, roughly half attending online, primarily from the US due to COVID travel restrictions. Over 30 participants from the US were supported by the NSF travel grant, Award #ECCS-2218933.

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

1. Data analytics, Machine Learning/Artifical Intelligence (ML/AI) methodology, and digital twin modeling for future grid performance visibility;
2. The grid and Distributed Energy Resource (DER) monitoring, control, and protection challenges to meet the zero-carbon goals;
3. Control and communication architectures and requirements for increased grid safety and reliability;
4. The market challenges in integrating DERs into the zero-carbon grid of the future.

The Workshop organizational details – workshop goals and objectives, the individuals from the Organizing and Steering committee from the US and Europe, are provided in the introduction.

Topic 1 "Data analytics, ML/AI methodology, and digital twin modeling for future grid performance visibility" discussions **(Section 2)**, point to the issue related to the integration of "communities of edge AI." The presenters' emphasis was on security and data privacy, high-fidelity modeling, hierarchical optimization and operation, and the use of big data. The research area suggestions focused on tools and mechanisms for knowledge transfer, power grid models with massive grid-edge resources, and modeling risk prediction using big data. The gaps and barriers ranged from a lack of understanding of how data-driven and physics-based models can be integrated to the need to introduce simplicity and scalability in the modeling tasks. Sharing and building public data sets is recognized as the most urgent need.

Topic 2, "The grid and DER monitoring, control, and protection challenges to meet the zero-carbon goals" discussions (**Section 3**) – highlight the complexity of interfacing DERs with Inverter based Resource (IBR) control and having to do with low-inertia grid properties. The more and faster data streaming from millions of sensors and public policy to enable DER participation in the markets is also emphasized. The research area suggestions include the need for holistic methods that integrate more tightly control and protection requirements and the necessity to focus on the net-zero carbon grid as the overall goal. The gaps and barriers include limitations of the current communication, control, and measurement architectures and the need to develop data-driven methods that are robust to data uncertainty and inaccuracy. Understanding of the dynamics of the integrated networks with prevalent IBR control and market interactions of such dynamic DERs are mentioned as the gaps.

Topic 3, "Control and communication architectures and requirements for increased grid safety and reliability" discussions (**Section 4**) explore the cyber-physical control and communication architectures with increasing edge devices expected in the future. The roadmap for European Technology & Innovation Platforms (ETIPs) and Smart Networks for Energy Transition (SNET) is presented as an example of major infrastructure architecture undertakings in Europe. The research area suggestions include extending the network monitoring of DERs for greater situational awareness and providing behind-the-meter resource monitoring capabilities. The need for more comprehensive tools for Transmission and Distribution (T&D) data management and coordination for DERs services, including stationary and mobile energy storage management, is also recognized. The gaps and barriers range from lack of adequate cyber-physical security solutions considering edge to the need to overcome the resistance to adopting new technologies and DER interface practices. The need to have adequate AI/ML models for addressing limitations of existing physics-based power grid applications, scalable cyber-physical testbeds for validation, and for exploring new EV, energy storage, and IoT technologies is also emphasized.

Topic 4 "Market challenges in integrating DERs into the zero-carbon grid of the future" discussions (**Section 5**) point to the issue related to the design of "future markets with massive DERs." The presenters emphasized local energy markets, market coordination, flexibility and resilience, and resource adequacy. The research area suggestions include autonomous and scalable grids, decentralized risk management, close coordination between T&D networks, prioritization and benefit quantification of grid services provided by DERs, and inclusion of equity and affordability of electricity in market design. The gaps and barriers range from social and behavioral issues to the need to update the regulatory framework to advance new solutions for energy prices, tariffs, rates, and contracts, and eventually to enhance the technologies for real-time control of DER flexibility.

The cross-cutting topics, not explicitly discussed by the Workshop participants as a separate topic but widely mentioned by the presenters – are spatiotemporal scalability of control, protection and motoring architectures, the new modeling approaches that fuse data- and physics-based models, high-resolution sensors for better assessment of the dynamics of DER interfacing – with the grid, modeling of weather impacts, and regulatory framework that allows new markets for procurement of DER services. The research area suggestions for cross-cutting issues include market designs that are more socially aware and take a more comprehensive view of consumer behaviors and needs. The risk-based analysis that helps better manage the DER flexibility with renewable generation uncertainty and variability and how to achieve a tradeoff between centralized and distributed grid control, combined with technologies that inherently meet cybersecurity requirements, are a few other mentioned research areas. The gaps and barriers focus on the (1) need to explore the impacts of the grid reliability on the resilience of other critical infrastructures (transportation, telecommunications, food production, manufacturing, finance, etc.), (2) the need to include behavioral and social aspects into the grid regulatory framework, and (3) the data availability and variety that are not readily used today.

The report concludes with **Section 7** – "Future steps," stating that the experience from the joint US-European Workshop has shown some commonalities and some differences in the approaches – it is recommended that future workshops be held to explore the synergies further.

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.

1. Introduction

1.1. Background

This US-European Workshop is a continuation of the PSerc and NSF-sponsored Forum/Workshop titled "Grid at the Edge: Interfacing Legacy Grids Operated by Utilities with Emerging Grid Components Owned and Operated by Third Parties" held in Oct 2020/March 2021. The NSF report that came out of the earlier NSF-sponsored Workshop identified several areas of future research interest but did not focus explicitly on the technological means for achieving the seamless integration of distributed energy resources (DERs) with the utility grid. Particularly it did not address the need for new decision-making tools that enable the market, utility, and DER operators to manage a seamless operation of the integrated grid.

This US-European Workshop was focused on defining topics for future research on grid visibility, safety, and reliability using synchronized sampling and data analytics technology. The goal was to explore research gaps and barriers in developing the new monitoring, control, and protection infrastructure that will enable the operators, market participants, and energy consumers to draw the benefits of the renewable energy resources contributing to the zero-carbon grid-of-the-future.

The FERC Order 2222 in the USA has paved the way for the DER owners and aggregators to work with the utility and market operators in achieving the reliable and safe operation of the integrated grid. A similar regulatory framework has been the focus of 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 explore how synchronized sampling and data analytics technology may contribute to the integrated grid visibility, ultimately leading to improved future grid safety and reliability.

The traditional energy management systems (EMS), market management systems (MMS), and advanced distribution management systems (ADMS), as well as protection systems, have been supplemented with synchrophasor technology and advanced data analytics – to create wide area monitoring, protection, and control (WAMPAC) solutions – which have offered recognizable benefits in the transmission system over the last decade – but have not been explored for the applications in the distribution and DER systems. The open research question is how the future development in synchronized sampling and data analytics technology may contribute to grid visibility, a necessary condition for the reliable and safe operation of the integrated grid. This research question ultimately leads to how the suite of monitoring, control, and protection decision-making tools needs to evolve to meet the future needs of a zero-carbon integrated grid.

The Workshop discussion aimed to define the needs of the future grid stakeholders, including market, utility, and DER operators. The Workshop participants from academia, utility, manufacturers, consultants, and funding agencies focused on defining research directions, questions, gaps, and barriers.

The cybersecurity discussion was out of scope. A ***list of the Workshop discussions topics is***:

1. Data analytics, ML/AI methodology, and digital twin modeling for future grid performance visibility;
2. The grid and DER monitoring, control, and protection challenges to meet the zero-carbon goals;
3. Control and communication architectures and requirements for increased grid safety and reliability;
4. The market challenges in integrating DERs into the zero-carbon grid of the future;

1.2. Organizational Details

The Workshop Agenda:

May 23, 2022: 15:00-19:20pm CEST (UTC+2), Discussion Topics 1&2

May 24, 2022: 15:00-19:20pm CEST (UTC+2), Discussion Topics 3&4

NSF Support: Travel Grant for the participants from the USA (10 in-person and 30 online attendees)

Workshop Host: The Independent Transmission Operator of Croatia-HOPS. Their representative was the invited Keynote for the IEEE-sponsored SGSMA2022 conference held back-to-back with the Workshop.

Date and Location: May 23-24, 2022; Split, Croatia (in-person event with online attendance by exception only), back-to-back with the IEEE-sponsored Intl. Conf. on Smart Grid Synchronized Measurements and Analytics, SGSMA2022: https://www.sgsma2022.org/ held May 24-26, 2022

Attendance: 24 Moderators/Speakers and over 50 attendees from academia/ industry/ government, all by Invitation only

Sponsorship: National Science Foundation-NSF and SGSMA Association

Organizing Committee:

US side: M. Kezunovic (Co-Chair), Texas A&M University; A. Chakrabortty (NSF Coordinator); Anjan Bose, WSU; Joe Chow, RPI; Vijay Vittal, ASU; Yilu Lu, UTK; Oren Shmuel, Berkeley; Mark McGranaghan, EPRI;

European side: Christian Rehtanz (Co-Chair), TU Dortmund, Germany; Mario Paolone, EPFL, Switzerland; Lars Nordstrom, KTH, Sweden; Carlo Muscas, UNICA, Italy; Patrick Panciatici RTE, France; Igor Ivanković HOPS, Croatia; Lorant Dekany, entso-e, Belgium;

Steering Committee:

US side: Chen-Ching Liu, VT; Evangelos Farantatos, EPRI; Christopher Irving, DOE; Jeff Dagle, PNNL; Ben Kroposki, NREL; Hamed Mohsenian-Rad, UC-Riverside; Damir Novosel, Quanta

European side: Antonio-Gomez Exposito, U. of Seville, Spain; Nikos Hatziargyriou, NTUA, Greece; Jovica Milanovic, Manchester University, UK; João Peças Lopes, INESC, Portugal; Pierre Pinson, DTU, Denmark; Lucas Saludjian, RTE, France; Goran Strbac, Imperial College, UK; Louis Wehenkel, Université de Liège, Belgium.

Outcome: Joint US/European Report

Workshop registration fee: 100 Euros for Europeans and $120US for US participants

Workshop venue: RADISSON BLU RESORT & SPA, SPLIT, CROATIA

COVID-based Exemptions: The attendance in person was expected. The online attendance was only accommodated as needed to meet government/employer regulations in effect at the time of the event.

2. Topic 1: Data analytics, ML/AI methodology, and digital twin modeling for future grid performance visibility

2.1. Presenters' Emphasis

The theme of presentations in this panel was geared toward the unprecedented challenges in (1) building and operating communities of edge AI in power grids ranging from data privacy and security at the grid-edge, consensus-driven continual learning within a network of edge AI, and communication requirements, (2) realistic high-fidelity modeling of power grids with communities of edge AI through automated, data-driven digital twins to understand the real-world operations and control, (3) the hierarchical operation and control optimization in power distribution grids with the proliferation of heterogenous grid-edge resources, and (4) the use of big data analytics to predict the state of risk and decision-making on the utilization of flexible loads and other available grid-support resources during emergency conditions to deliver resilience services.

2.2. Research Area Suggestions

The panel presentations and the ensuing discussions suggested a number of research areas that need further exploration. Research should focus on (1) establishing tools and mechanisms for knowledge transfer within a community of grid-edge AI, taking into account the incorporation of human knowledge in model learning and correction of AI-in-production, and (2) establishing fast, transparent, and user-friendly models for power systems with massive grid-edge resources and autonomous AI agents to understand the multi-time scale operation and control processes within the evolving power grid and its interdependent systems, (3) establishing tools and mechanisms that harness the full potential in big data analytics for risk predictions and risk-informed operational decision-making in the face of emergencies.

2.3. Gaps, Barriers, and Desired Outcomes

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

- There is a lack of understanding of how the data-driven and physics-based models complement each other. How to integrate and hybridize traditional model-based solutions with new computational advances (such as ML), data sciences (DS), and digital twins (DT) is lacking. For example, physics-based models and human knowledge can potentially improve the generalizability and transfer learning capability of ML solutions. The current approach blindly applies existing generic ML solutions and fails to effectively incorporate useful models and knowledge.
- Among all ML/DS applications at the grid edge, a notable need is to improve simplicity and scalability by reducing the communication and computation overhead in order to achieve low-energy consumption. This niche of research is still largely missing in the grid edge environment.
- Given the human interactions and decisions in the grid-edge environment, it is important to promote cross-disciplinary research between engineering, social sciences, and policies. Additionally, there is a lack of behavioral studies on how the individuals (customers, system operators) may perceive and respond to the state of risk in the system. Nonetheless, it is challenging to establish such collaborations due to the disciplinary differences.
- And one lasting challenge is to incentivize data sharing and build public datasets.

3. Topic 2: The grid and DER monitoring, control, and protection challenges to meet the zero-carbon goals

3.1. Presenters' Emphasis

The theme of presentations in this panel was geared toward the unprecedented challenges in this area that stem from (1) reduced/low inertia in power systems, (2) proliferation of distributed energy resources (DERs) and inverter-based resources (IBRs) in the grid, (3) more and faster data streaming from distributed sensor networks and underpinning data-driven methods, and (4) public policy broadening energy market participation. These challenges will impact grid reliability in transmission and distribution systems such as frequency and voltage stability, protection systems, and power quality – and incentives for coordinating DERs and other IBRs such as distributed control and optimization algorithms between and within T&D territories that will require reliable communication networks and standards.

However, the presenters also shared how these challenges beget new opportunities to broadly re-think power system operations and reliability. Specifically, the growing availability of fast and responsive IBRs or wind-generating turbines represent new types of resources that rapidly can provide active/reactive power and dynamically enhance system stability. In addition, geographically dispersed DERs can be coordinated at scale and has the potential to provide numerous grid services locally (distribution) and globally (transmission) that can improve system reliability and resilience by being responsive to a variety of grid, carbon, and/or price signals.

3.2. Research Area Suggestions

Numerous technical and practical challenges with transitioning from conventional to low-inertia and zero-carbon power system operations define relatively unexplored research areas. In general, the discussions centered on (1) holistic methods that are cognizant of today's conventional operations (e.g., protection systems), (2) the capability of DERs and IBRs, and (3) future (carbon) market reforms. Specifically, the following research areas were suggested:

- Methods and tools for data-driven, grid-aware control of DERs in low-inertia grids need to identify flexibility limits, robust against data uncertainty, and account for cyber-security, power quality, and privacy concerns. In addition, sensor siting techniques are needed to account for multi-timescale sampling rates to increase observability.
- IBR active/reactive power control methods need to account for protection systems and vice versa in a holistic fashion, which requires new unified models for analyses and optimization and coordination techniques for protection systems. This extends to developing a new paradigm for contingency (e.g., N-1) and islanded operations and restoration that draws an equivalence between many having small IBRs/DERs and just one large thermal power plant.
- Markets need to be developed to account for local (distribution) and global (transmission) control objectives while enabling equitable and inclusive participation of DERs based on carbon, price, and/or grid signals. This could extend to markets for data to overcome data/control asymmetries across zero-carbon energy systems (T&D and Aggregators).
- Increase collaboration between US and EU academic institutions towards finding novel solutions for zero carbon energy systems and DER/IBR control.

3.3. Gaps, Barriers and Desired Outcomes

In developing rigorous and scalable methods that drive energy systems to meet zero-carbon goals, there exists the following fundamental gaps and barriers:

- Coordinating a large number of DERs and IBRs will depend on access to reliable and secure data, communications, sensing, and computing at operational timescales spanning milliseconds to hours and spatial scales of low voltage distribution nodes to high voltage ISO territories/regions/states.
- Data-driven methods will also be difficult to implement in an uncertain environment and/or low-quality measurements and forecasts.
- The impact of power electronics and aggregations of IBRs and DERs will speed up system dynamics and analyze protection systems, power quality, and contingency operations, a major challenge. In particular, the interaction between inverters (specs, capabilities, and control) and protection is largely unexplored due to a lack of unified models and overreliance on siloed engineering approaches.
- Market reforms need to account for multiple actors (TSO, DSO, Aggregators, Device Owners) with asymmetrical information/data and control about DERs and the grid, making grid-aware/cognizant control of DERs challenging to accomplish.
- Overall, the data ownership structures and differences in communication capabilities across different parts of the grid (e.g., different utilities) will make it difficult to share data and align incentives to ensure inclusive and equitable participation in the green transition.

4. Topic 3: Control and communication architectures and requirements for increased grid safety and reliability

4.1. Presenters' Emphasis

Panelists in this session focused on control and communication requirements and alternative architectures for grids with high penetration of edge devices. The theme of presentations included (1) cyber-physical architecture for control and communication with integrated and distributed information systems, (2) trajectory for the evolving grid, (3) activities and roadmap for European Technology & Innovation Platforms (ETIPs) Smart Networks for Energy Transition (SNET) and (4) holonic architecture for the resilient power grid.

4.2. Research Area Suggestions

Panel presentations and follow-up discussions suggested a number of research areas, including (1) developing and analyzing a network of integrated information devices using distributed information systems for extended situational awareness, (2) enabling behind-the-meters (BTM) DER clusters to work together to supply the grid services with coordinated and integrated cyber-physical management, (3) tools and mechanism for integrated T&D data management and analysis considering generation and load on both sides including static and mobile storage.

4.3. Gaps, Barriers, and Desired Outcomes

The panelists identified several gaps, barriers, and desired outcomes:

- Cyber-physical security analysis needs to be extended to the edge considering all the components, including sensors, communication network, information architecture, power grid substation devices, power grid applications, and control.
- Existing cyber-physical testbeds have limitations due to modeling limitations, assumptions, approximation, and resource limitations for scalable system simulation. Additional work is needed for high fidelity, large-scale cyber-physical testbeds, and scalable control.
- Grid is moving from tight coupling (Rigid/Brittle with event propagation) to loose coupling (Agile/Flexible) system with diffused capital ownership. Energy storage, EVs, and IoTs are the next wave of innovations and must be coupled with system aggregation and/or service aggregation.
- Key aspects of the future grid will be to ensure energy justice and decarbonization.
- Transmission and Distribution (T&D) should no longer be discussed separately and should be considered an integrated electricity delivery system (EDS).
- New technology to address the cyber-physical power grid with active edges needs support from the markets, and the market needs support from the policy.
- Holonic architecture for resilient power system operation is needed to support diverse services based on operating scenarios.
- Integration of more devices at the bottom of the energy system requires a middleware that interfaces between the bottom and the top. We should not further introduce interdependencies when adding a diverse number of devices, applications, and functionalities. We cannot control everything, and bottom layer control needs to be more autonomous with visibility, transparency, and synchronization capability.
- Some rules provide a shield and a legal boundary for technology adoption. Organization transformation research has been brought up as an important topic for research. The technical and policy research should not be in silos.
- Data explosion is happening with local cybersecurity practices and needs to be utilized better.
- A lot of AI/ML tools are nascent in their development. We need to exercise caution when we use them to solve our problems, especially at the grid edge but with broader visibility.

5. Topic 4: The market challenges in integrating DERs into the zero-carbon grid of the future

5.1. Presenters' Emphasis

The presenters emphasized the following aspects for future electricity markets:

- Local energy market: As DERs are allowed to participate in the electricity markets, there are many discussions about setting up local retail electricity markets, distribution system operators (DSOs), and the hierarchical primary/secondary/prosumer-level electricity markets for the distribution grids in order to handle DER market activities, ensure distribution grid operational security and preserve prosumer privacy.
- Market coordination: To enable optimal interactions between wholesale and retail/local markets, one needs to address the coordination among the wholesale markets, retail/local markets, DSOs, primary/secondary/prosumer-level market services, virtual power plants (VPPs), DER aggregators, and tariff components.
- Flexibility: Due to the increased uncertainty of renewable generations, more flexibility is needed at different timeframes for various purposes. New flexibility products need to be defined. Flexibility must be coordinated across different services, at different wholesale/regional grid levels, and between different entities to avoid conflicting market signals.
- Resilience and resource adequacy: future market designs need to provide market signals to facilitate grid resilience and stimulate necessary investments for resource adequacy.

5.2. Research Area Suggestions

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

- Design autonomous energy grids that are agile and flexible with massive intelligent controllers at the grid edge.
- Frameworks and operational business model innovation for integrating DERs in the wholesale markets.
- Massive scaling of intelligent field devices, interconnection standards and common grid architecture layers.
- Decentralized risk management via edge technologies by enabling consumers to privatize risk by offering real options on the demand side.
- Identifying customer needs and preferences.
- Integration and coordination between transmission and distribution systems and with other energy sectors via proper market design.
- Protecting consumers against high price volatility in the retail/local markets.
- Prioritization and benefit quantification of grid services provided by DERs.
- Equity and affordability of electricity should be accounted for (or at least evaluated) in market design. There are significant positive externalities associated with universal access to electricity, and the goals of equity and affordability should be incorporated in more technically-focused models.
- Market design to stimulate necessary investments for resource adequacy.

5.3. Gaps, Barriers, and Desired Outcomes

Several approaches have been proposed for local energy market designs, coordination between different market entities, and unlocking demand-side flexibility. The following fundamental and practical gaps are identified: (1) the scalability of the algorithms/market designs for handling massive DERs; (2) the practical challenges of business model innovation for DER market integration; and (3) the coordination of flexibility services for different purposes across multiple timeframes, multiple geographical dimensions, different grid levels, and different market entities.

The discussions have suggested the following desired outcomes for future electricity markets: (1) providing flexible services in a scalable, affordable, secure, and resilient way; (2) enabling decentralized risk management via edge technologies and real options on the demand side; and (3) reflecting the true value of DERs and true needs of the consumers via proper designs and coordination of energy prices, tariffs, rates, and contracts.

6. Crosscutting issues

6.1. Presenters' Emphasis

The cross-cutting issues were not covered in a separate discussion but were extrapolated from the discussions on each topic. However, the following observations seem to be mentioned by the presenters in almost all of the theme discussions: (1) The scalability of the control and communication systems is dramatically different from the legacy system and system with millions of DERs and billions of data points that may be faced in the future, (2) The scalability requires new modeling techniques that will fuse physic- and data-based models, (3) To account for the future grid dynamics, high-resolution sensors are needed across T&D systems and DERs, (4) Spatiotemporal modeling of weather impacts needs to be coupled with spatiotemporal high-precision measurements enabled by time-synchronized sampling, and (5) the regulatory framework have to enable wholesale and retail market transactions that are overseen by separate transmission and distribution independent system operators.

6.2. Research Area Suggestions

The research areas for crosscutting research were not emphasized explicitly, but an integration of various research disciplines was repeatedly mentioned as needing further research. A few particularly important cross-cutting research areas are mentioned in the discussions:

- The market studies should explicitly include the social equity and societal goals for consumer-oriented market incentives for the trading of consumer-owned DER services
- The AI and ML modeling approaches need to have a tight correlation to the physical system modeling to create the physics-informed data models with their digital
- The behavioral studies are needed to further understand the reaction of electricity consumers and DER owners to the grid emergencies such as outages and other contingencies
- The legacy grid IT architectures have to be integrated with the IoT architectures where DER may be primarily interfaced
- Due to the variability and uncertainty of the renewables, the risk-based approaches should be explored to predict the state of risk of centralized and distributed energy resources
- A balance between centralized grid control and agent-based distributed control needs to be explored to manage responses to local and system-wide future grid events
- Cyber-physical security, while intentionally excluded from the scope of the Workshop, was mentioned as an undelaying design goal for the future grid at the edge interfacing

6.3. Gaps, Barriers, and Desired Outcomes

By looking at the discussions on the different topics, some barriers, gaps, and desired outcomes seem to apply to all the themes:

- The legislative and regulatory framework in the US and Europe needs to be extended to accommodate a variety of new developments introduced by the proliferation of DERs
- The interfacing of DERs requires further development of the industry standards that will more explicitly define the requirements that the owners of the grid and IBRs need to meet

- The market structure needs to advance beyond current wholesale transactions and include transactions at the consumer level that are fair and socially equitable
- The DER resources behind the meter need to be managed to offer sufficient information to the Aggregators and grid owners to enable them to manage their expectations of DER services
- While an abundance of data coming from higher fidelity sensors placed in utilities and outside databases are becoming available, the data sharing policies and tools are missing
- The modeling of the future power grid needs to move beyond physics-based models into data-driven models, but such outcomes are still not widely pursued
- The utility of the future will look dramatically different from the current utility, so the roadmaps on how to make the transition need to include a holistic view of critical infrastructures interfacing
- While the practices in the US and Europe are aligned in many aspects, when it comes to DER interfacing and market development, further collaboration will benefit both sides

7. Future steps

7.1. Open Issues

While the Workshop discussion was fairly broad, a few issues did not get proper attention simply due to the lack of time. A few such areas are as follows:

- The electricity system is a backbone for many other critical infrastructures (transportation, water, manufacturing, agriculture, finance, etc.), so the interdependencies need to be explored
- Cyberphysical security is a must in the future grid and how to design and implement security-aware solutions across all DER interfacing options remains a challenge
- Behavioral, social and equity aspects of the future grid modeling need to be considered together with the physical grid representations and data models to account for the variety of unforeseen interactions and adequately model risk
- The net-zero carbon grid has many aspects that need to be more explicitly defined through harvesting DER flexibility to meet renewables variability and uncertainty
- Making the future grid more observable will require the use of data from more precise sensors and other seemingly unreeled yet crucial databases (weather, vegetation, social media, etc.)

7.2. Next Joint US-European Workshops

Continuing the practice of Joint US-European Workshops was overwhelmingly supported by the Workshop participants. The US and European researchers are encouraged to propose future topics and involve NSF and similar European research agencies in supporting such workshops regularly.

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

Appendix A: Workshop Program

Moderator #1	Moderator #2	Participant #1	Participant #2	Participant #3	Participant #4
Topic #1: Data analytics, ML/AI methodology, and digital twin modeling for future grid performance visibility					
Ben Kroposki (US), P	Patrick Panciatici (EU-France), P	Mladen Kezunovic (US), P	Anamika Dubey (US), O	Peter Palensky (EU-Netherlands),P	Ricardo Jorge Bessa (EU-Portugal), P
Topic #2: The grid and DER monitoring, control and protection challenges to meet the zero-carbon goals					
Mario Paolone (EU-Switzerland),P	Wanda Reder (US), P	Joe Chow (US), P	Line Roald (US), P	Keith Bell (EU-UK), P	Cancellation
Topic #3: Control and communication architectures and requirements for increased grid safety and reliability					
Lars Nordstrom (EU-Sweden) P	Mark McGranaghan (US), P	Chen-Ching Liu (US), O	Michael Pesin (US), O	Nikos Hatziargyriou (EU-Greece), O	Christian Rehtanz (EU-Germany) , P
Topic#4: The market challenges in integrating DERs into the zero-carbon grid of the future					
Richard O'Neill (US), P	Jean-Michel Glachant (EU-Italy), P	Anuradha Annaswamy (US), O	Elisabeth LaRose (US), O	Anke Weidlich (EU-Germany), P	Norela Constantinescu (EU-Belgium),O

P- In person **O-Online**

Topics:

1. Data analytics, ML/AI methodology, and digital twin modeling for future grid performance visibility;
2. The grid and DER monitoring, control and protection challenges to meet the zero-carbon goals;
3. Control and communication architectures requirements for increased grid safety and reliability;
4. The market challenges in integrating DERs into the zero-carbon grid of the future;

Agenda (All times are in Central European Standard Time-CEST):

May 23:

- 15:00-17:00, Topic 1
- 17:00-17:20, Coffee Break
- 17:20-19:20, Topic 2

May 24:

- 15:00-17:00, Topic #3
- 17:00-17:20, Coffee Break
- 17:20-19:20, Topic #4

Scribes assignment

TG: Travel Grant ***P: In-person*** ***R: Remote***

#	Name	School	TG	Contact email	Topic
1	Payman Dehghanian	George Washington	P	payman@email.gwu.edu	#1
2	Richard Zhang	UI-Urbana Champaign	R	ryz@illinois.edu	#1
3	Hao Zhu	UT-Austin	R	haozhu@utexas.edu	#1
4	Mads Almassalkhi	Univ. of Vermont	R	malmassa@uvm.edu	#2
5	Junbo Zhao	Univ. of Connecticut	R	junbo@uconn.edu	#2
6	Bolun Hu	Columbia Univ.	R	bx2177@columbia.edu	#2
7	Anurag Srivastava	Washington State Univ.	R	anurag.srivastava@mail.wvu.edu	#3
8	Jianhua Zhang	Clarkson Univ.	R	jzhang@clarkson.edu	#3
9	Quanyan Zhu	NY Univ.	P	qz494@nyu.edu	#3
10	Meng Wu	Arizona State Univ.	R	mwu@asu.edu	#4
11	Chiara Lo Prete	The Penn. State Univ.	R	cxl63@psu.edu	#4
12	Timothy Hansen	South Dakota State Univ.	R	timothy.hansen@sdstate.edu	#4

Notes:

- The session format is 45min for the presentations (8-10min per presenter), 10-15min Q/A by the Moderators, and 1h for audience interactions and follow-on Q/A.
- Introductions by Moderators should be minimal since the bios are posted. Each presenter should introduce themselves and the organization during their presentation
- Moderators will contact the presenters and share any prepared questions. For efficient interactions, one moderator may be focused on the Q/A with the presenters and the other with the audience
- If any slides are to be used, no more than 5 slides should be prepared by any presenter. The slides should be shared with the moderators and organizers by May 16, and will be posted on the website
- The session discussions will NOT be recorded to assure free exchanges. 12 scribes (three per each topic) will capture the discussion notes, which will be used to create an NSF Workshop Report
- The report will be created by the team of scribes led by the Workshop Co-Chairs. The report will NOT have any attribution to the source of the comments, and will be shared with all for feedback

The goal of the Workshop is to identify research topics for the next 5-10 years. The focus is on research fundamentals, gaps and barriers, practical implications, and US/European

Appendix B: List of Ateneeds

Invited attendees

Name	**Organization**	**US/EU**	**Participation**	**NSF Grant**
Moderators/Panelists				
Ben Kroposki	NREL	US	In-person	n/a, SC
Patrick Panciatici	RTE, France	EU	In-person	n/a, OC
Mladen Kezunovic	Texas A&M Univ.	US	In-person	n/a, OC
Anamika Dubey	Washington State Univ.	US	On-line	Yes
Peter Palensky	Delft Univ., The Netherlands	EU	In-person	n/a
Ricardo Jorge Bessa	INESC, Portugal	EU	In-person	n/a
Mario Paolone	EPFL, Switzerland	EU	In-person	n/a, OC
Wanda Reder	Grid-X Partners	US	In-person	Yes
Joe Chow	Rensselaer Polytechnic	US	In-person	Yes, OC
Line Roald	Univ. of Wisconsin	US	In-person	Yes
Keith Bell	Univ of Strathclyde, UK	EU	In-person	n/a
Antonello Monti	Aachen Univ., Germany	EU	In-person	n/a
Lars Nordstrom	KTH, Sweden	EU	In-person	n/a, OC
Mark McGranaghan	EPRI, USA/Ireland	US	In-person	n/a, OC
Chen-Ching Liu	Virginia Polytechnic	US	In-person	Yes, SC
Michael Pesin	DOE-OE	US	Online	n/a
Nikos Hatziargyriou	NTUA, Greece	EU	Online	n/a, SC
Christian Rehtanz	TU Dortmund, Germany	EU	In-person	n/a, OC
Richard O’Neill	ARPA-E	US	In-person	n/a
Jean-Michel Glachant	Florence School of Regulation, Italy	EU	In-person	n/a
Anuradha Annaswamy	MIT	US	On-line	Yes
Elisabeth LaRose	GE	US	In-person	n/a
Anke Weidlich	University of Freiburg, Germany	EU	In-person	n/a
Norela Constantinescu	entso-e, Belgium	EU	On-line	n/a
Remaining Organizing Committee Members				
Aranya Chakrabortty	NSF	US	Online	n/a
Anjan Bose	Washington State Univ.	US	Online	

Vijay Vittal	Arizona State Univ.	US	Online	
Yilu Liu	UT-Knoxville	US	In-person	
Shmuel Oren	UC-Berkeley	US	On-line	Yes
Lorant Dekay	entso-e, Belgium	EU	On-line	n/a
Steering Committee				
Hamed Mohsenian-Rad	UC-Riverside	US	On-line	Yes
Damir Novosel	Quanta Technology	US	In-person	n/a
Christopher Irving	DOE-OE	US	Invited	n/a
Jeff Dagle	PNLL	US	Invited	n/a
Pierre Pinson	DTU, Denmark	EU	Online	n/a
Goran Strbac	Imperial College, UK	EU	Online	n/a
Carlo Muscas	University of Cagliari, Italy	EU	In-person	n/a
Sara Sulis	University of Cagliari, Italy	EU	In-person	n/a
Ninoslav Holjevac	University of Zagreb, Croatia	EU	In-person	n/a
Igor Ivankovic	HEPS, Croatia	EU	In-person	n/a
Jovica Milanovic	Manchester University, UK	EU	Invited	n/a
Lucas Saludjian	RTE, France	EU	Invited	n/a
NSF Travel Grant Recipients				
Saeed Lotfifard	Washington State Univ.	US	Online	Yes
Payman Dehghanian	George Washington Univ.	US	In-person	Yes
Junbo Zhao	Univ. of Connecticut	US	Online	Yes
Qifeng Li	Univ. of Central Florida	US	Online	Yes
Chen-Ching Liu	Virginia Tech	US	In-person	Yes
Anurag Srivastava	Washington State Univ.	US	Online	Yes
Sara Eftekharnejad	Syracuse University	US	Online	Yes
Le Xie	Texas A&M Univ.	US	Online	Yes
Hao Zhu	UT-Austin	US	Online	Yes
Anu Annaswamy	MIT	US	Online	Yes
Masood Parvania	University of Utah	US	Online	Yes
Chiara Lo Prete	The Penn. State Univ.	US	Online	Yes
Na Li	Harvard	US	Online	Yes
Bolun Hu	Columbia Univ.	US	Online	Yes
Paras Mandal	Univ. of Texas at El Paso	US	Online	Yes

Anamika Dubey	Washington State Univ.	US	In-person	Yes
Quanyan Zhu	NY Univ.	US	In-person	Yes
Ramteen Sioshansi	Ohio State Univ.	US	In-person	Yes
Timothy Hansen	South Dakota State Univ.	US	Online	Yes
Richard Zhang	UI-Urbana Champaign	US	Online	Yes
Baosen Zhang	Univ. of Washington	US	Online	Yes
Sukumar Kamalasadan	Univ. of NC at Charlotte	US	Online	Yes
Jianhua Zhang	Clarkson Univ.	US	Online	Yes
Mahnoosh Alizadeh	UC-Santa Barbara	US	Online	Yes
Line Roald	Univ. of Wisconsin	US	In-person	Yes
Mads Almassalkhi	Univ. of Vermont	US	Online	Yes
Meng Wu	Arizona State Univ.	US	Online	Yes
Shmuel Oren	UC-Berkeley	US	Online	Yes, OC
Hamed Mohsenian-Rad	UC-Riverside	US	Online	Yes
Marija Ilic	MIT	US	Online	Yes
Ming Jin	Virginia Tech	US	Online	Yes
Yan Li	The Penn. State Univ.	US	Online	Yes
Chengzong Pang	Wichita State Univ.	US	Online	Yes
Wanda Reder	Grid-X Partners	US	In-person	Yes
A. Ramapuram-Matavalam	Iowa State Univ.	US	Online	Yes
Leigh Tesfatsion	Iowa State Univ.	US	Online	Yes
Rajasekhar Anguluri	Arizona State Univ.	US	Online	Yes
Joe Chow	Rensselaer Polytechnic	US	In-person	Yes, OC
Other Participants/Invitees				
Britta Buchholz	Hitachi Energy, Germany	EU	In-person	n/a
Thibault Prevost	RTE, France	EU	Online	n/a
Mark O'Malley	Global PST Consortium	EU	In-person	n/a
Asja Derviskadic	Swiss Grid, Switzerland	EU	In-person	n/a
Efthymios Karangelos	Univ. of Liege, Belgium	EU	In-person	n/a
Sara Sulis	Univ. of Cagliari, Italy	EU	In-person	n/a
Ricardo Prata	E-Redes, Portugal	EU	OnLine	n/a

Note:

NSF – National Science Foundation

OC - Organizing Committee

SC - Steering Committee

US – United States

EU - Europe

Appendix C: Scribe notes from discussions on Topic 1

Topic #1: Data analytics, ML/AI methodology, and digital twin modeling for future grid performance visibility;

Panel Moderators:

Ben Kroposki (National Renewable Energy Laboratory, USA)

Patrick Panciatici (France)

Panelists:

Ricardo Jorge Bessa (Portugal)

Peter Palensky (Netherlands)

Anamika Dubey (USA)

Mladen Kezunovic (USA)

Scribes:

Payman Dehghanian (USA), compiled comments into this document.

Richard Y Zhang (USA)

Hao Zhu (USA)

Ricardo Jorge Bessa of INESCTEC first discussed the "**challenges to build communities of edge AI in power grids**."

In particular, he introduced the global challenges irrespective of the focused application as:

- The operation of *heterogeneous networks and devices*, that possibly require combining heterogeneous data.
- The knowledge should circulate and grow in communities of edge AI, which itself adds additional complexities in
  - Data Privacy & Security
  - Consensus (collaborative vs. competitive learning)
  - ICT constraints and requirements
  - Capacity to learn contextual information
- Maintenance of edge AI with hundreds to million agents, which require correction procedures (to incorporate feedback from the end-use) and trust from humans.
- Energy use and consumption requirements of the edge infrastructure to run AI

One possible application was introduced as "***Edge Digital Substation***", where:

- Smart Alarm Processing can detect abnormal operation of protective devices, alarm segmentation, and assist human manual actions.
- The main challenges in this application included:
  - The ability to combine heterogenous data
  - Frugal AI where only a small % of data is useful

    - Revival of the expert systems to assist humans
    - Ontologies to increase data & model interoperability

Another use case application was introduced as "***Energy Time Series Federated Modeling***" with particular focus on RES forecasting and predictive maintenance, where the goal is to extract knowledge by combining data of different owners. The main challenges in this application arise as follows

- The ability to perform collaborative online learning to ensure data privacy
- The ability to hybridize the expert systems and data-driven knowledge

A third use case application was introduced as "***DER Local Control***" with the main focus on data-driven control of DERs and automated parameter tuning. The main challenges in this application arise as follows

- The ability to perform maintenance and continuous monitoring of multiple AI agents
- The ability to perform continual learning and update the learned parameters as data shift in time
- The ability to ensure consensus and coordination to reach a global optimum

He introduced the future ***R&D directions*** as follows. Some applied to the grid edge environment and some to the control room environment.

- To establish a mechanism for knowledge transfer at the edge community level
- To pursue an Interdisciplinary approach for trustworthy edge AI
- To enable correction of AI in production: observing problems in AI should not result in abandoning it, but retaining and correcting it.
- To enable integration of human knowledge in model learning and correction using symbolic reasoning; that is a hybridization of expert systems and data-driven knowledge.
- To design and develop mechanisms to reduce energy requirements of edge AI. Examples include spiking neural networks, TinyML, physical neural networks or hybrid physical-digital systems.
- To approach cross-silo federated learning without losing simplicity
- To enable distributed and hierarchical sequential decision processes

Anamika Dubey of WSU discussed "**Active power distribution systems: changing systems operation with grid-edge resources**".

In particular, she focused on the operation of the system interfacing complex edge devices and resources for the first time, posing challenges to system reliability and stability. She introduced the systems operation challenges in 3 main categories:

- Changing nature and requirements of the grid at the edge: new systems calling for new optimization and control tools
- Scalability for interconnected T&D systems
- System of systems complexity that engenders multiple subsystems with different operation motivations and objective functions

The coordination of grid-edge devices by integrating data, measurement, and control should be leveraged to optimize the distribution operations for grid-services, addressing:

- Nonlinearity
- Heterogeneity
- Time-scale separation

- Real-time data processing

The distribution grid control and optimization processes at the grid-edge will have to address the following challenges:

- Algorithmic bottlenecks
- Ownership boundaries and privacy concerns
- Information unavailability and uncertainty
- Visibility and situational awareness

Model-based approaches should be merged into data-driven solutions for decision-making. This is because each approach alone has its own shortcomings. In particular,

- Model-based methods have limited capability in handling fast dynamic systems
- In model-based methods, computation complexity increases drastically with network size
- Data-driven approaches are limited in processing high dimensional data
- Data-driven approaches ignore constrained physics-based environment

The need for an open-source library of (centralized and distributed) solutions at the distribution level that establishes a connection between model-based and data-driven AI techniques in the control and optimization processes was highlighted, which calls for further research and development.

At the end, she emphasized the dual challenge of rapid decarbonization and resilience to climate change, for which new solutions using the data/measurements from and control over the grid-edge resources could be developed.

A summary of discussions and ***R&D directions*** are provided below:

- The state-of-the-art research has provided lots of interesting works on autonomous control. Future research should not reinvent the wheels, but complement the existing state of knowledge.
- What is found lacking in the literature is how to model distribution systems with high levels of inverter resources. How do we optimize operations when considering different control modes? How do we reduce complexity of autonomous operations with a large number of edge devices? What is the visibility level required across the network, not requiring every measurement to be available for learning to be successful? What are the alternative unconventional ways of using AI to enable the system operation in nontraditional ways?
- State estimation is required and challenging in the new environment. Future research needs to look into the algorithms needed to perform these services either in a centralized, decentralized, or distributed fashion.

Peter Palensky of TU Delft discussed "**Digital twins in power system operations**".

Digital twins were introduced as the mainstream technology of tomorrow, that mimics the automated real-world operations and control, and envisioned to be performed ubiquitously in the cloud or at the edge.

- Digital twins enable running the system into the future and see, fast and accurately, how it will perform mimicking the real-world conditions.
- The types and usage of digital twins were discussed in a variety of applications (model-free, static, and dynamic) and over different timescales (slow, real-time, and faster-than-real-time). Fastest and dynamic twins are used for controls, while fast and static twins are used for forecasting applications.

- The twin needs to be data-driven, embedded, and automated to be able to gain insights on the systems operation and performance. Accordingly, validation, convergence, transparency, and explainability of digital twins were highlighted as the main challenges.

The ***model requirements*** and challenges to enable digital twins in power system operation are

- Faster digital twins come with additional complexity (hidden states, emerging behaviors) that should be addressed.
- They are cyber-physical models including discrete IT/OT elements as well as continuous physics and physical equations.
- They should reflect multi-physical systems (heat, power, gas).
- They should enable multi-timescale performance evaluations capturing the requirements of edge power electronics, hydraulics, etc.
- They should capture the system and event uncertainties including those around rate high-impact events.

The bottom line is that digital twins bring together numerical vehicles, stuffed full of data, equations, white and black-box models, solvers, different users and decision makers (technicians, analysts, planners, and operators) to interface with and learn from real systems and people. The end goal is to assess complex power systems.

Mladen Kezunovic of Texas A&M University discussed "**State-of-Risk Data analytics and net-zero carbon grid: what is the synergy?**".

In particular, he emphasized:

- The reality of flexible loads that follow generation: how flexible loads help meet uncertain renewable generation in the grid. In other words, with the considerable cost of power outages and a power grid with proliferation of renewables, the main question to address is how to leverage the more flexibility available on the customer side to respond to the outage-inducing events. That is, if I know the resources I have available at the edge (non-grids) and some information of the outages with prediction models, then the question is how to use the former to support the loads and minimize the outages?
- Different modalities of power outages, impacts of power outages, and the role of weather as one main cause of power outages, evidenced by the February 2021 event in Texas, were discussed.
- One key R&D direction was introduced: ***effective use of data analytics to improve resilience through risk predictions***. The resilience enhancement measures should include hazard characterization, vulnerability assessment, system management and mitigation strategies. In particular, if one can predict a state of risk (SoR), the mitigation can be performed ahead of schedule, thus improving resilience.
- With the main goal to improve resilience through risk prediction, the main challenge is establishing the correlation between the outage causes and related data (vegetation indices, animals' data, weather forecasts, utility measurements, network assets, social media mining, and lightning data, among others).
- The SoR can go beyond the electric power system, incorporating all interdependent systems and services. For example, a shortage of gas may be translated in an outage event, creating imbalances in the market, and necessitating remedial actions.

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

- How Big Data models "translate" to (outage) predictions of State of Risk (SoR)?

- How (outage) predictions may be used to utilize the flexibility (SoR mitigation)?
- How spatiotemporal SoR (outage) prediction scales to petabytes (Big Data), mesoscale (10-1000km spatial granularity) and flexible time horizons (millisecond to years)?

In response to the introduced research questions, a number of ***gaps and barriers*** exist that should be tackled:

- There is a lack of understanding on how the data-driven and physics-based models complement each other? Big Data management tools and high-resolution physics-based models are currently unavailable.
- A fundamental SoR framework for use by utilities, market operators, aggregators and DERs is lacking. Practices to assure utility (industry) acceptance and preparedness are unavailable.
- There is a lack of behavioral studies on how the individuals (customers, system operators) may respond to SoR? Multi-and cross-disciplinary teams to tackle the fundamentals adequately are needed.

Summary of Panel Discussions and R&D Directions:

- ***Resilience metrics*** are needed that capture different decisional contexts: different spatial and temporal needs and requirements. Also, metrics are needed to capture and quantify the system-level as well as locational resilience.
- The need for ***scalable and self-learning state estimation*** in complex less-visible distribution systems was highlighted. Even state estimation in the transmission grid requires lots of manual tuning.
- Hierarchical ***(layered) optimization and distributed control*** tools are needed to address the evolving complexities in the network. The challenges will be on how to define different layers, how to define interaction boundaries, etc. Addressing these challenges require different tools than the traditional agent-based modeling techniques.
- One main challenge is to deal with ***scale***. The operation margins are being eroded. Is it now time to think of *graceful failure*?
- There is this view of putting data in a centralized reposition. The question then arises on how to ***incentivize data sharing***?
- Using data-driven approaches is good, but one can argue that in many cases, classical ***model-based methods*** work better than blind ML. Along with the emphasis on data-driven AI, efforts should be also geared toward modeling complex systems previously not modeled.
- The privacy-preserving distributed optimization algorithm is already a well-established literature. Ideas around consensus-based transactive energy through iterative exchange of data and information (i.e., negotiating back and forth, offering a price through Lagrange multiplier and preserving the privacy of the customers) have been well researched. Future research direction should account for, guided by, and deviate itself from the ***previous efforts and existing literature*** in distributed optimization and control. A big part of the report should be highlighting the existing state of knowledge.
- Splitting of responsibility through hierarchical decision making requires an understanding on which people have access to what data/knowledge and who wants to use the information, what kinds of actions the data enable, etc. ***Regulatory frameworks*** are needed to prevent the "evil corporations" from exploiting the customer data for financial gains and benefits.
- "Humans" and ***human engineering*** are centric to any decision-making involving data analytics and AI applications. The question is how to apply a self-learning eco-system with many distributed systems with zero engineering? Engineering such an evolving ecosystem is time-costly. Even in

autonomous systems, human engineering is needed to design them and they cannot be ruled out of the equation.

- Science is ahead of reality in many applications. In power systems, it is the reverse. Our methods are behind the real-world systems and requirements considering the fast growth of the complexity with different dynamics. However, the power systems community has not well articulated the ***problems that need ML/AI and data analytics***. Big data was mentioned for the first time in our community more than 10 years ago! We better define the problems that have not been solved and search out what exists to help.
- An example of ML exists in the protection systems: relays have access to high-resolution measurements and can analyze using computations. Protection systems are inspired by "thinking globally and acting locally", and this should be the way how to approach ML.
- Little intelligence in the distribution system exists. What is the right level of intelligence needed? This requires research and thinking on application of Big Data analytics and optimization. Additionally, how does the intelligence get distributed? How do they become centralized? And how does the data flow and communication work are the challenges?
- ***Social sciences*** should be involved because humans are involved in decision-making. In distribution systems, we are dealing with the private sector that behaves emotionally not necessarily economically or rationally.
- Three main research questions are outlined: (1) how to move (the roadmap) from centralized to a decentralized setting for optimization and control? (2) Multiple owners exist and how should the data circulate? (3) ML is not yet a tool that can be used online.
- Another research question regarding distributed control is focusing on algorithms to work for agents that are not necessarily looking at system-level objectives (with different objectives, ownership boundaries, etc.). One solution might be investigating ***distributed digital twins*** and then analyzing if the local actions can be disastrous to the system performance before implementing the action in practice. It gives birth to ***adaptive learning*** so it evolves as the system operating states evolve.
- Future research should also focus on developing tools that are ***implementable*** as easily and quickly as possible by system operators. The electric utility industry does not have enough support nor resources to jump into an innovative ecosystem (different from Uber). So, the question is how can we make it easy for operators to use and implement the research right as they are developed and not 10 years later.
- Last note, moving away from a variety of tools already existing in practice should be well justified. The grid operator has 20 different tools and 20 different models. The solution is for the relevant data to be entered only once and get used globally as needed in different applications.

Appendix D: Scribe notes from discussions on Topic #2

Topic 2: The grid and DER monitoring, control and protection challenges to meet the zero-carbon goals

Panel Moderators:

- Mario Paolone (Switzerland)
- Wanda Reder (USA)

Panelists

- Keith Bell (UK)
- Joe Chow (USA)
- Line Roald (US)

Scribes:

- Mads R. Almassalkhi (USA), was not present but compiled comments into this document.
- Junbo Zhao (USA)
- Bolun Xu (USA)

Presenters:

Keith Bell : The grid and DER monitoring, control and protection challenges to meet the zero-carbon goals

The presenter shared their overarching vision of challenges around a low-inertia power systems: observability, controllability, and different timescales. Recently, significant reductions in inertia have causes frequency stability challenges and under frequency load shedding

There is a need to investigate proper protection system settings whose adaptiveness is critical for system stability and to avoid wide-area blackout.

The frequency response from inverter-based resources (IBRs) would also significantly enhance the system stability, if being successfully delivered. There are requirements in the UK (and many other countries are coming on board with their own requirements) that IBRs need to regulate both active and reactive power or provide voltage droop control at the point of common coupling.

Flexible resources can help the grid without significant investments on power network reinforcement and, thus, the question is how to harness them and ensure the reliable delivery when needed.

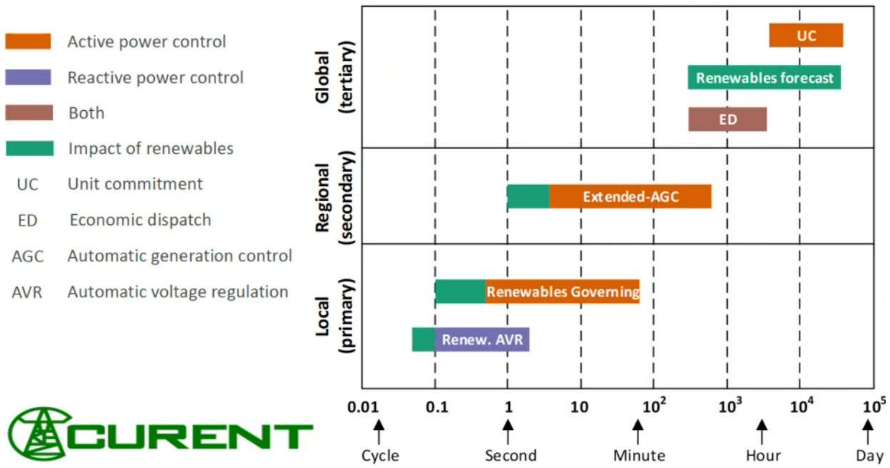
In case of grid outages, the islanded operation and black-start capability could drastically enhance the grid resiliency. This is supported by an enormous area of research in AC microgrids.

Co-optimization of active distribution system and transmission systems is another R&D area that enables the flexibility from distributed energy resources (DERs) for grid services, such as frequency containment reserve, restoration reserve, regulating reserve, contributing to local system operations, e.g., voltage support as well as the optimal utilization of power network and generation assets. The open questions/challenges include:

- What are salient measurements, including siting and sampling? Note that not all measurements need to have high sampling rates and, thus, the optimal placement considering different sensor types is valuable to consider.
- More broadly: how to address the observability and controllability issues?

Joe Chow (US): Enabling Inverter-Based Resource Control in Power Systems with High Renewable Penetration

Conventional AC power systems rely on generator inertia and reactive power support via excitation control to provide buffer area for relays and control to operate reliably. With more IBRs integrated into the grid, it is challenging to overcome the low inertia and weak grid issues. However, the benefits from IBRs are that they can provide fast active and reactive power control, see the figure below.



In the U.S., ERCOT (ISO in Texas) requires all generators, including wind turbine generators (WTGs) to provide frequency support (5% droop with deadband of 17 mHz) and WTGs can hold back 3% of generation for frequency reserve market. The reserve is dispatched via AGC signals as setpoints. Proper control of WTGs and other IBRs would enhance the frequency stability of the systems. That is, WTGs' active power control enhance transient stability of the grid due to fast control of power injections. A possible control is to reduce WTG active power output during the fault and ramp it back gradually to full power, so that it acts like a "braking resistor" (like BPA's Chief Joseph braking resistor in Pacific NW).

The new power system paradigm on operation and control with a large number of IBRs requires more reliable and robust PMU data and communications. Tools are needed to leverage these data to enhance and improve power system operations.

In addition, there are also some other challenges to be addressed:

- Aggregation & Coordination of many small-scale (kW-scale) DERs/IBRs to achieve active power control design on bulk power systems
- Protection & Coordination: optimal settings of protection relays and coordination among protection systems.
- Contingency analysis: how to define N-1 contingency when grid-services that used to be served by large-scale power plant are replaced by aggregated IBRs/DERs? E.g., is a line outage followed by trips of multiple IBRs accounted as a single contingency (CA solar generation dropouts) or multiple contingencies? How many IBRs tripping constitutes a contingency? We will need to consider a new paradigm in contingency analysis of low-inertia systems?

Line Roald (US): Distribution Utilities and DER Control: Benefits and Challenges

FERC order 2222 directs regional grid operator to allow aggregators of DERs to access the bulk energy market. This requires a complicated coordination (and DER control architectures) between regional grid operators, distribution utilities, and DER aggregators. At a minimum, distribution utilities need to ensure that DER control does not cause any operational violations while DER aggregators aim to provide an aggregated response to transmission system needs without having the distribution system operational limits in mind. This calls for the development of effective "grid-aware" or "network-aware" coordination schemes for DERs to achieve (global) transmission system objectives while respecting the (regional/local) distribution system operational constraints.

It is essential to identify the grid flexibility limits considering the operational constraints. This could be cast as a (multi-level) optimization problem.

There are some fundamental questions about how distribution utilities could and should interact with DERs in their grid?

- In day-to-day operation, how should distribution utilities seek to enable or restrict DER control by other entities? Is it via local market or grid control signals?
- Who has access to which network and DER data in making decisions? DER aggregators and/or utilities? How to satisfy data privacy and cyber security concerns? Do Utilities have to be the ones controlling DERs?
- In normal maintenance scenarios, can distribution utilities leverage available DERs to support local microgrids and reduce cost of maintenance?
- In post-disaster restoration, can distribution utilities leverage available DERs to support local microgrids and reduce duration of load shedding. Location of DERs can significantly change the optimal restoration plans and the ability of DERs to form microgrid may drastically reduce load shedding.

Discussion Sessions:

<u>High level topics:</u>

- Risk assessment: On longer timescale. identify the vulnerabilities and proactively prepare for that, such as infrastructure investment, social aspect considerations. On shorter timescales, prediction-enabled proactive control and optimization can support reliable grid operations, but there are fundamental challenges with predictions when facing more extreme (and unpredictable) weather events?
- How to ensure fairness in the objective function and outcome evaluations when managing DERs, such as design of customer incentives and control algorithms?
- How to keep customers informed about their electricity (carbon and prices) and an possible curtailment sustained during extreme events?
- DSO Example (UK): Locational marginal price and enhanced resilience for distribution system operators will be moving closer to reality, as distribution system operators will be installing meters in LV networks in coming 5-10 years to monitor congestion.
- Splitting up control of distribution system via a designated DSO and DNO may enable proper control of local assets. DER control architectures need to reflect potential operational models.
- EVs will be important loads to coordinate and reliable communication links and coordination schemes are needed.
- What are effects on the grid with a lot of uncontrollable resources? In defining reserves for the planning stage, the uncertainties in reserves can be considered but this may be costly (worst-case scenario)
- DER aggregator vs. Utility: to investigate/test/validate different methods, it would be helpful to have access to open-source data sets, so we can investigate how to best share information from DSO to aggregators and the effect of different incentives on distribution grid, transmission grid

services provided by DERs, and understand possible DER (prosumer) participation models. This leads to important questions around quantifying flexibility.

- How to coordinate different power electronic devices and understand their interactions? How do we (IEEE PES) promote coordination of topics related to control and protection, and how do we enable this, such as test systems, IEEE task force, etc?

Specific questions:

Q1 *- local flexibility increases the complexity of coordination for TSO, managing local resources vs. grid. Can the distribution company be part of the service?*

A1 - aggregator, local resilience, California safety shut-off

A2 - tribal community. PV/Gen/Storage only powers owner home, overcome safety issues into community microgrid/power neighbors. Protection is a big issue. Regulatory questions are challenging to answer. Utilities don't want to rely on customer assets to provide reliability.

Q2 *- Can we apply solutions from transmission grid operations to distribution grids?*

A1 – Low fault currents and (meshed) distribution structure provides challenges. How to site DERs (utility?) and operate the distribution grid with DERs? Who can operate the DERs?

A2 - No clear picture of how to do this as siting and operations are interconnected problems. We need methods suitable for (real-time, online) data analytics. What are the risks in operation, risks can be addressed by both operational objectives and planning objectives?

A3 - Risk metrics are mostly long-term, and need predictive risk metrics

A4 - Aggregators are agnostic and communicate with TSO with bids

A5 - Network cost recovery is based on energy, not power, everyone pays more with PV.

Q3 *- How will monitoring, control, and protection philosophy change in the future with lots of DER? How to respond and prepare proactively for high-impact, low-probability (HILP) events?*

A1 - anticipate risk of events requiring long restoration times, and what can be done in advance. Risk-based approach.

A2 - the social aspect of disturbances, DSO does not wish to leverage demand-side resources for grid resources. Only interested in controllable resources.

A3 - behavior, critical consumers rely on electricity need information to deal with outage events during emergency scenarios. Vulnerable customers need higher priority/protection from emergency curtailment/load-shedding. School systems depend on school districts, house prices are left behind low-income. Wealthy communities can insulate themselves. This brings up systemic equity challenges with "smart grid" that are mostly unanswered today.

A4 - UK examples, new regulatory periods 2023-2028 distribution operators will install monitors in medium-voltage grids, need to provide information to manage congestion via market rules. Use of LMP at LV and MV networks. 2) resilience is on the agenda, DO will provide plans to enhance resilience for their networks; 3) separations between DSO and DO to provide proper control and planning in local networks.

A5 - Operation and restoration. Resilience-as-a-service: send diesel generators to provide local supply and storage. Not a technology issue, whether willing to do it. Need hardware and software to coordinate. NYS can restore power in no time, and NYC has community microgrids. JFK community with four generators to provide local resilience. EV.

Q4 *- What happens if we deploy DER, EV, and battery that are not controllable* (*red*. by whom?)

A1 - spatial granularity and variability depending on what to do.

Q5 - *No integration framework for customers to participate in the planning process. Which protocols are needed for information exchange, efficient deployment, and engagement with customers?*

A1 - one ISO has started implementing FERC 2222, while Aggregators are work to predict how to participate.

A2 - Should DSO share grid operating states with aggregators - real-time state estimation is shared with (all) aggregators? TSO does not do this as it reveals system vulnerabilities.

A3 - Market models for incentives, why should utilities share anything and what do DSOs get? How to define a business model that everyone is incentivized to collaborate. Control mechanism to make this work. Behavior side to incentive side. Cross boundaries, regulatory frameworks, and incentives. Investors.

Q6 *- Can we imagine in the future performing grid operations and planning on the timescale of minutes compared to the current 5- and 15-minute base? Today's timescales of ms to hours are supported by traditional generators. The impact of power electronics and the role of aggregators will change this paradigm. Intraday automatic trading could be sped up? As a comparison, today's TSO -> DSO -> windfarm operations is achieved in the order of a couple of minutes today.*

A1 - at a faster time scale, automatic control is too fast for system operators to react. Utility staff, regulators and consumers have to overcome the legacy mindset. On the dispatch side, the dispatch interval depends on how fast to solve the dispatch optimization problem. NYISO's balancing market can solve at 15 minutes interval, now 5 minutes, due to computation speed, faster computer, and better software and renewable forecasts. NYISO sometimes sends set-points to generators directly and provided forecasted LMPs 3 hours out to ensure a fairer participation from participants.

Q7 *- Measurement uncertainty: If data-based modes are used to manage the grid and the data contains dynamics/harmonics/noise how must the models account for these uncertainties and help operators manage the risks?*

A1 – This is a timescale question. Depends on how close one gets to the system limits. Control is based on slow dynamics (i.e., not hard) today. As more DERs enter the picture, the response could become too fast as power electronics devices interact with each other and automatic trading may lead to issues.

Q8 *- When we get these interactions between control and protection, how to promote interdisciplinary solutions to protection, control, and DER coordination together? Today, conventional protection systems and power electronics require novel control schemes? Should be an interaction between protecting people and controlling system. How to design protection and control hand-in-hand? How to make sure these interactions happen and where do we start with an IEEE task force?*

A1 - the issue is the tools for designing control devices and assuring safety of people are not compatible. The system studies are very difficult to set up on these two tools. No unified model for power systems in research. Need to choose tools based on the specific study.

A2 – Need well-informed assumptions: Behavior modeling, Locational marginal carbon emission signal. How far can we get by controlling/influencing/incentivizing people and what are challenges/complexities associated with people?

A3 - Have protection people and power electronics people talk with each other more often. Evaluate options and simulate behaviors from PE and protection into cost-benefit analyses.

Q9 *- What can be done to control new resources, grid-forming inverters, dynamic, monitoring and control come together.*

A1 - resource do not recognize ride-through faults, and because the grid and DERs depend on each other, the coordination eventually breaks down.

A2 - ISO/DSO, the ride-through could be a problem.

Q10 *- important to have the budget for communicating results for research, because only work if society understands. Social science research, communicating why protection, etc. is important.*

A1 - contradictory, need to be technical to solve problems but may lose audience (i.e., low impact work that no one uses).

A2 - policymakers for emission reduction are an example.

Q11 *– Must flexibility and renewables be market-based via balancing controls? Markets do not have geographical information. Do market-based solutions increase complexity?*

A1 - reliability, and safety in markets. Range of potential outcomes.

A2 - market-based solution for DER control with equity in mind. Making markets work in an equitable way so more people benefit from DER coordination.

Appendix E: Scribe notes from discussions on Topic 3

Moderators

- Lars Nordstrom (Sweden)
- Mark McGranaghan (USA)

Panelists:

- Chen-Ching Liu (USA)
- Michael Pesin (USA)
- Nikos Hatziargyriou (Greece)
- Christian Rehtanz (Germany)

Scribes:

- Anurag Srivastava (USA), compiled comments into this document.
- Jianhua Zhang (USA)
- Quanyan Zhu (USA)

Chen-Ching Liu discussed the architecture of information, communications, and control for decision-making. A network of integrated information devices (IIDs) deployed in the system can help with extended situation awareness using distributed information system (DIS). Contingency analysis is an example of vulnerability assessment. Self-healing mechanism mean how to reconfigure the system in response to serious events to reduce the loss in an automated manner. DER control is obvious scenario in the Microgrids, but the unobvious scenario is with the high penetration of DERs. How to build the control capability here of these DER clusters and enable them to work together to supply the grid services? Next big architecture change is in the transmission and distribution grids. The generation resources and storage systems are moving into the distribution system and can provide T&D services. There is a need for data to achieve these goals. The distribution information system is promising. We can create integrated information devices by consolidating all the information into one device including all measurements. With the information system, we move toward a cyber-physical system and create an integrated model of communication models and the power system models. The detailed modeling of the computer behaviors (e.g., queueing systems) in the communication systems can allow us to understand the effect of latency on a cyber-power system. What tool we have: existing tools like NS3 have some limitation. Testbed is not good enough and simplification for continuous time plant (with linear system model and measurement, h) and discrete time controller (with communication delay, t). Flexible loads with different levels of complexity to be integrated into decision making and another layer is aggregator. Third component is database from weather and new sources needed (e.g., tree) to be integrated within.

Michael Pesin indicates that grid trajectory is moving from tight coupling (Rigid/Brittle with propagation) to loose coupling (Agile/Flexible) and capital diffuse systems. Energy storage, EVs, and IoTs are the next wave of innovations. We need to have some system aggregation and service aggregation. SAE and IEE communities need to work together on standards that are integrable. Security must to be considered in the design process of the energy systems. One effort is to ensure the energy justice. Everyone can participate in the community energy considering economics and take advantage of this with solutions like the blockchain or energyshed. Another project is about the very ambitious goal of zero-carbon. There are alternative to transmission lines to move the renewable energy, such as complex power flow controllers, dynamic topology configuration, and optimizing the power flow in the system. We are not talking about the T&D separately anymore and talking about EDS (electricity delivery system). You have to manage both your generation and load on both sides, and you should have the system capability to have control mechanisms on both sides. The future grid should be variable, integrative, and flexible across the Transmission and Distribution and Customers. Energy storage and solutions such as machine learning will be important. We need to have the new protection system considering the evolving grid with resources in both sides of EDS. Resilient distribution systems and the future grid architecture will be an important research topic. A lot of efforts have been done in the model development, North American energy resilience model. This model includes some interdependent infrastructures, such as nature gas and communications and other a few. New technology needs the support from the markets and the market needs the support from the policy. Basic Sciences to commercialization: Technology, Markets and Policy are needed.

Nikos Hatziargyriou focused on the distribution system ETIP SNET roadmap in Europe. Estimated investments in European distribution grid until 2030 includes the digitalization through modernization, smart meters, and automation; resilience, and energy mobility. Europe has set the priority to support the revolution of the energy system and market to improve the reliability and resilience. Now Europe is preparing the roadmap document for 2022 to 2031. These 9 high-level use cases (HLUCs) will be provided to the groups and projects. The HLUC 1 is about the optimal cross sector integration and grid scale storage. The HLUC 2 is about the market driven TSO-DSO system under interactions. The HLUC 3 is about the European wholesale markets, regional and local markets, and how their cooperators coordinate. The HLUC 4 speaks about massive penetration of RES into the transmission and distribution grid. Then HLUC 5 is about the power electronics and simulation methods, and next one HLUC 6 is focusing on transportation integration and storage to support the network. Next three years, focus will be on the HLUC 7 about the enhance system supervision and control including cyber security (PPC 2022-2025). It includes the next generation of TSO control room, DMS, measurements and GIS and wide area monitoring, control, and protections.

Christian Rehtanz discussed about the holonic architecture for resilient power system operation. Main idea is that the different level in between layers provides different services based on operating scenarios and different service needs basic active and reactive power flow control. The basic idea is to define one part of the system in a holon. In such holon, every part in the system is at the specific grid level. This grid level has some instant connectors to it, like energy management system, household wind power system on the specific level, they provide the kind of flexibility. They don't want to share their data or whatever they have, and they want to optimize themselves and provide flexibility in the significant outsides, either from the market or from the grid operation. Similarly, the grid level below as itself provide the flexibility, controllability, and the below level can organize by themselves and there is no reason for them to get information about everything below. The instance is taking care of the supervision and coordination of the entire holon, interconnection of computer units, autonomous control, or responsible control center with the distributed database. The holonic structure in the sense of self-similarity and scalability of power system related to Grid structures, communication architectures, distributed data and shared digital twin structures, and distributed and autonomous control, operation and market functions.

Discussions:

Identity and Authentication: There was a question about digital identity, i.e., how to know the identity of a digital entity. How to keep it safe when you enter a contract to fulfill the delivery of a service. Blockchain technology can be a potential way to address the problem but may not completely resolve the identity issue.

Design Architecture:

- The panel argues that the bottom-up approach matters. When we introduce more devices at the bottom of the energy system architecture, we need to have a middleware view that interfaces between the bottom and the top.
- The holonic architecture can be thought of as a system of systems, containing many structured agents. The agents have local transactions, and they interact to achieve high-level functions. The panel agrees that one key element of the architecture is to draw boundaries in the large-scale system,

decompose it into smaller systems, and delegate each subsystem to a specific function. This design has to balance resiliency and functionalities.

- It is important to note that we should not further introduce interdependencies when adding a diverse number of devices, applications, and functionalities. It is hard to control from the bottom level. We need automation at the bottom.
- What is the best way to control the millions of DERs? There is the gap between the academic papers about the distributed Virtual Power Plant (VPP) and the practice.
- How do operators deal with the 5G, 6G and AI. We cannot control everything and need to be more autonomous with visibility and transparency.
- Dealing with power system and addressing transformational aspect is very challenging.
- Decentralization does not mean that subsystems can do whatever they like. The design is to impose a structure, delegate responsibility, and fulfill the tasks.

Policy for Organization Transformation: There are rules that provide a shield and a legal boundary. Organization transformation research has been brought up as an important topic for research. The technical and policy research should not be in silos. We need to encourage transdisciplinary research across NSF divisions. There are challenges to doing social experimental research in many contexts.

Edge Services- Data Management and AI:

- Data explosion happening with local cybersecurity practice. Imagine two million of meters moving from 15 minutes to 1 second (e.g. synchophasor) and look at aggregator and weather data. With data stress, how to design and support this data explosion?
- Smart meter has so much data and what are you doing with that? Application will drive sensors.
- Management of uncertainty is important when having resources at the edge?
- Differentiating service from edge is important.
- Increasing diversity for edge services enables resilience.
- Big data stream and not a big data (see work done at the Google, Amazon): size may not be the only question; property is important.
- Note that a lot of AI/ML tools are nascent in their development. We need to excise caution when we use them to solve our problems.

Appendix F: Scribe notes from discussions on Topic 4

Topic #4: The market challenges in integrating DERs into the zero-carbon grid of the future

Moderators:

- Richard O'Neill (US)
- Jean-Michel Glachant (Italy)

Panelists:

- Anuradha Annaswamy (USA)
- Elisabeth LaRose (USA)
- Anke Weidlich (Germany)
- Norela Constantinescu Belgium)

Scribes:

- Meng W (USA)
- Chiara Lo Prete (USA)
- Timothy Hansen (USA)

Anuradha Annaswamy has emphasized:

- Overarching drive
    - 100% renewables across the globe
    - Biden administration with goal of 45% solar power by 2050
    - FERC Order No. 2222 to open wholesale markets to distributed resources
- Local retail electricity markets
    - Motivation: Customers act as price takers in today's wholesale-utility-customer model. Customers have no interaction with the market. The values/services provided by customers are not appropriately compensated/accommodated.
    - Question: Can we go toward a local retail market?
    - Presenter's proposal:
        - ✓ Hierarchical local electricity markets (LEM) with the primary market, secondary market, and consumer market
        - ✓ Each of the three markets provide situational awareness to three levels of operators across the distribution grid
        - ✓ The three levels of distribution markets are coupled with the consumer edge through IoT
        - ✓ Each level of market operator manages its resiliency score and commitment score
        - ✓ All levels of market operators need to honor the physics of the grid, by providing accommodations to different grid operational challenges introduced by different distributed assets (demand response, storage, etc.)
        - ✓ Primary market with distributed optimization, secondary market with multi-objective optimization, consumer market with federated learning

- ✓ Primary market:
- Interactions between the substation and nodes on the primary feeder
- Objective is to minimize operating costs and line losses, maximize social welfare
- Constraints: nonlinear convex branch flow model on balanced and radial networks with operational and capacity limits
- Fully distributed (proximal atomic coordination algorithm)
- Computationally tractable
- Reduced communication
- Preserve data privacy
- Market clearing period to compensate both real power and reactive power by D-LMP
- ✓ Secondary market:
- Interactions between the primary nodes and secondary nodes
- Co-exist with the primary market
- Objective: minimize net cost to secondary market operator, disutility to consumer market operator, maximize aggregate flexibility and reliability
- Constraints: operational power limits, power balance between secondary market operator and primary market operator, real-time tariff, and budget balance
- ✓ Consumer market:
- Deals with the flexibility, dependability, security, and privacy of each consumer
- Provide incentive for consumers while preserving consumer privacy
- Federated learning to train global model with local data
- ✓ Next steps:
- At present: address unbalanced and meshed networks, penalty structures for third-party entities not honoring their commitments, multi-period optimization for EV and V2G, validation using HELICs, HIL, ADMS, consumer market design accommodating consumer preferences (double auction tools, game theoretic tools), day ahead markets, ancillary markets, uncertainty, security wraps
- Vision: Autonomous energy grids that are agile and flexible, affordable and equitable grid that is secure and resilient, billion end-point control
- Towards implementation: who will be implementing/in charge of these markets – utilities, third-party aggregators, public utility commission? ISO-DSO interactions, how to interconnect with bulk grid.

Questions from the audience and related answers

- o Question #1: Who is choosing/optimizing the grid configuration in your design?
  - ▪ So far, we have been choosing an electrically co-located structure for the ease of exposition. It could be possibility implemented because there are already the topological constructs in the cyber layer in order to add the analytics.

    - It does not have to be like this because market structures could be different. We need to think about what the appropriate partition is. The issues about dealing with digital identity and having secure information transfer would probability determine how this hierarchical market structure needs to be segmented.
- Question 2: How much information gets passed between the market participant and the market clearing process?
    - Market bids are followed by schedules.
    - There is a larger interval of flexibility that is provided by market participants. The final market clearing comes back with a shorter interval which meets all the other grid requirements.

Elizabeth LaRose has raised the following points:

- Innovation focus areas for research to come into products
    - Operation optimization
        - ✓ Maintain reliability and resiliency
        - ✓ Market designs to harvest flexibility from DERs
        - ✓ Visibility, modeling, controllability of DERs
    - Grid stability
        - ✓ Device management system – ADMS, DERMS
    - Performance optimization
        - ✓ Wholesale and retail markets, virtual power plants (VPPs), aggregators – appropriate price signals, FERC 2222
- Proactive DER planning – research needs
    - DER hosting capacity: understand how much more DERs can be managed by a given feeder, or where interconnection costs may be low/high → demand forecasting and electrification projections
    - Locational net benefits analysis: determine the specific benefits of specific services at a specific location to guide prosumers and developers → energy shifting and congestion management
    - Defer traditional infrastructure investments through non-wires alternatives that provide specific services at specific locations → peak management, inertia, voltage support, resource adequacy, resiliency
    - Assess true value of DERs to inform rate- and tariff-making decisions and emerging DSO models → beyond load control signals, time-of-use (TOU) tariffs and net metering, to dynamic pricing and access to wholesale power markets (directly via FERC 2222 or via aggregators/VPPs)
    - Locational and temporal true value of DERs to inform tariff decisions
    - Prioritize DER and non-wires alternatives projects
    - Social aspect of DER grid integration: investment and ability/bankability of technology to allow applicability for a spectrum of consumers.

- US FERC Order 2222
  - Grant DER owners and aggregators wide-scale access to wholesale power markets
  - Promotes operational and business model innovation, VPPs
  - Enables the distribution system operator (DSO) platform
  - Unlocks flexibility provided by DERs, generally closer to demand and locational constraints, enabling valuable assets in net-zero carbon pathways
  - Under development:
    - ✓ Compliance plans for US ISO/RTOs and distribution utilities
    - ✓ Frameworks for integration into wholesale power markets for DER aggregators including DSO structures and bidding timeframes, operational business model innovation, power markets for DER aggregators (VPPs or direct access), how this framework will work on demand side, how to interact with the wholesale market platform.
    - ✓ Massive scaling of intelligent field devices, interconnection standards and common grid architecture layers (system of system): smart meters, SCADA, DERM, device management, cybersecurity.

Anke Weidlich has taken the following position:

- Flexibility and coordination
  - Most important concepts for the workshop: flexibility and coordination
  - Coordination can be achieved by market
  - Technical constraints in the market makes the coordination between many markets challenging
  - Coordination at the level of wholesale market works well with clearly defined product (energy delivery over time). European wholesale market is even free of congestion constraints. Congestion is managed afterwards through re-dispatch.
  - Wholesale market needs to evolve to facilitate transition toward net zero. Wholesale market needs to make sure the right investments are incentivized to achieve resource adequacy.
- Prosumer-level market integration
  - At the prosumer level, currently there is not many efforts for market integration.
  - Local energy markets/communities are motivated by prosumers' willingness to reduce energy cost and sell energy to neighbors.
  - Prosumer flexibility provision needs to be incentivized and activated by local energy communities/markets.
  - To activate local flexibility, the system view at different grid levels need to be properly reflected. Research efforts on the interactions between different levels of the grid are needed. Hierarchical energy market is one example to address these interactions.
  - Prioritization is needed on which entity/level can use the prosumer flexibility first. Coordination between the flexibility needs for different purposes/entities is needed.

- Flexibility products:
    - Flexibility products need to be defined and quantified.
    - We need to identify/define the seller and aggregator of flexibility products.
    - Hierarchy of flexibility provision: first consider local constraints, then higher level services can be provided.
    - Flexibility needs to be coordinated across different services. The coordination needs to make sure providing one service to one level/region does not compromise the grid energy balancing and operational security at a different level/region.
    - We need to derive flexibility products that support required services.
- Coordination of tariff components to facilitate desired outcomes/flexibility
    - Need incentives for system-supportive operation
    - Need emission factor/carbon signal
    - Interactions with the end customers need to be addressed. Simple tariffs will continue to play an important role. The tariffs need to be properly designed.
    - Difficult to achieve multiple conflicting goals simultaneously
    - Wholesale market signal may not be the most effective signal to incentivize end customers.
    - The tariffs need to be aligned with wholesale signals. The tariffs should set priorities for which purpose local flexibility should be used first.
    - Tariff components need to be coordinated to facilitate desired outcome.
    - Benefits of flexibility provision needs to be quantified to avoid equity issues.

Questions from the audience and related answers

- Question 1: Is the coordination needed for electricity markets only or for electricity markets with other markets (gas, solar)?
    - Coordination with other sectors are also needed. This will bring additional complexity to the problem.
- Comment 2: equity, poverty, and disadvantages can be addressed by other entities outside of the electricity sector.

Norela Constantinescu emphasized the following:

- More flexibility is needed due to uncertainties for the renewables/less dispatchable generations, electrification of heating/transportation/industries, and power electronics in the grid (with less predictable flows and lack of inertia).
- Flexibility is needed at different timeframes: real-time flexibility, short term flexibility, and long-term flexibility.
- Geographical/spatial dimension needs to be considered for flexibility provision. Flexibility provision for the energy flows is at the global level. Flexibility provision for the voltage supports is at the local level.
- Flexibility is needed for frequency control (inertia, fast frequency support), voltage control, congestion management, stability, system restoration, etc.

- Characteristics of the platforms that facilitate flexibility provision:
    - Multi-sided communication infrastructures
    - Facilitate data exchange between systems
    - Automated and scalable processes
    - Near real time responsiveness
    - Operated either independently or by network operators
    - Enable new products and transaction opportunities
- OneNet project – market coordination across EU
    - Provide market-based TSO-DSO coordination, market-based DSO-FSP (flexibility service provider) coordination, and technical TSO-DSO coordination
    - Real implementation
- Limitations of OneNet and research needs:
    - Challenges due to market coordination aspects, e.g. with regard to bids, rules for market settlement.
- Overall market challenges
    - Flexibility and market design regarding resource adequacy – stimulating the necessary investments
    - Resilience and efficient system operation – providing market signals in complex and distributed system of systems
    - Role of customer – identify different needs and preferences of customers
    - System of systems integration – integration with distribution systems and with other energy sectors via proper market design

➢ Questions from the audience and related answers

- Question 1: Can you comment on the EU model of treating transmission as constraints vs the US model of optimizing transmission via economic dispatch? Can EU market perform better if including transmission in the economic dispatch?
    - EU is moving toward enhancing grid capacity via new technologies to facilitate renewable integration (such as dynamic line rating).
    - There is ongoing discussion on introducing transmission constraints, but from a political side bidding zones are still preferred.
    - Not clear that the EU approach is underperforming compared to US.

1. Q&A Session

➢ Comment 1:

- EU use a lot of bus flipping to re-organize the network topology.
- A good framework to think about flexibility is from risk management perspective.
- Risk has been centrally managed so far, but now the edge technologies have enabled consumers to privatize risk by offering real options on the demand side, which can be mobilized to manage risk through a decentralized approach.

- Local markets can be leveraged to distributing the responsibility of handling risks.

- Question 2: Will retail markets transfer the risk of high price volatility to consumers? What is the appropriate approach to protect the consumers against high price volatility? How to ensure the equitable allocation of risk?
- One benefit of market is to create price liquidity and allowing participants to create hedging products.
- Exposing residential customers to price volatility is not wanted.
- Price liquidity provided by the market will enable distribution system operators or distribution utilities to create proper retail structure rates and hedging products. This could be one solution.
- Consumer flexibility will lower price volatility.
- Protecting the customers should not take away customer choice, because that is going to reduce volatility. Giving customers choice privatizes risk and enables them to pay what they want.
- The flexibility provided by customers are uncertain. We could deal with uncertainty and use uncertain resources in a capacity constrained system to achieve what we want (e.g., The overbooking mechanisms on airplanes can be adopted by power system).
- We don't just have to think about market design, but also contract design. This is an important aspect of risk management and has not been discussed.
- Need to ensure reliable/secure customer participation that does not compromise privacy.
- Question 3: Which grid service will lead to the most benefit for the retail consumers when they participate?
- DERs are more appropriate for short-term flexibility instead of long-term flexibility.
- Short-term needs can be first met by local markets.
- Question 4: What is needed to ensure equity/market access when homes/living areas are bought without knowledge of the grid topology or constraints?
- Location is important. We need to add towards property evaluation. We can skew the technology based on what one can deliver based on what flexibility can be enabled.
- There is a certain move in EU regarding the location and time for renewable supply (e.g., countries with a lot of renewables but not a lot of connections). Currently there is no strong common position across EU for this issue.
- Comment 5 on affordability:
- In the U.S. about 20% were struggling to pay for their energy bills in 2018.
- We need to make sure that affordability is kept in mind while designing new markets/contracts.
- Existing tools may accommodate equity considerations by incorporating equity/affordability into objectives or constraints of existing optimization models.
- There are social mechanisms that can compensate people who cannot pay for their electricity bills. Engineers cannot be made responsible for social outcomes. This is related to the current discussion in California. Markets should not be designed to solve social problems.
- How to measure equity/equitable access?
- Comment 6:

- We need to start looking at the risk and prediction of risk of losing power, and then working from there into mitigation measures, maybe some of the mitigation measures are regulated in the market. But we can’t just have the situation we had in Texas.
- Resource adequacy is the heart of this comment. Resource adequacy does need to be considered when you are paying through the market. Having a capacity component in the market mechanism could allow people to take into account the contribution of dependable capacity.
- Weather-related events and cyber-attacks are really challenging the resource adequacy.

➢ Question 7 on how to decide price in P2P trading?

- Not in favor of P2P trading at local level. During local congestions (such as multiple EVs charging at the same time), all EVs can agree on a scheme to coordinate their charging. The flexible participants can coordinate on how to use the constrained capacity.
- You can buy your neighbor’s electricity at whatever price you want.
- In local market (not P2P market) studies, the electricity price went down. This is not guaranteed but because of fine grain capture of location/time reduced overpayments to generators/utilities.