Pacific Northwest
NATIONAL LABORATORY

PNNL-31580

Distribution System Research Roadmap

Energy Efficiency and Renewable Energy

February 1, 2022

TE McDermott
BA Bhatti
K McKenna
M Emmanuel
M Heleno
SP Forrester

U.S. DEPARTMENT OF ENERGY
Prepared for the U.S. Department of Energy
Under contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312
ph: (800) 553-NTIS (6847)
email: orders@ntis.gov <https://www.ntis.gov/about>
Online ordering: http://www.ntis.gov

PNNL-31580

Distribution System Research Roadmap

Energy Efficiency and Renewable Energy

February 1, 2022

TE McDermott
M Heleno[b]
M Emmanuel[a]
K McKenna[a]
BA Bhatti
SP Forrester[b]

Prepared for
the U.S. Department of Energy
Under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99354

---

[a] National Renewable Energy Laboratory
[b] Lawrence Berkeley National Laboratory

Abstract

The scope of the U.S. Department of Energy's Energy Efficiency and Renewable Energy (EERE) office covers a number of distributed energy resource (DER) technologies, including distributed photovoltaics, smart buildings, wind, water, behind-the-meter-storage, and electric vehicles. The impact of these technologies on the distribution system is often assessed with an individual technology focus. Similarly, different technology offices often leverage different sets of tools, leading to analyses that are not comparable. EERE sought the ability to assess the impact of integrating multiple DER technologies, and to comprehensively address DER integration challenges across the portfolio of EERE technologies. This project built on existing work understanding technical challenges, mapped out the key research questions, assessed relevant capabilities across the national laboratory network, identified key gaps, and produced a research roadmap to inform EERE investment decisions.

Executive Summary

This report summarizes the technical challenges arising from increased distributed energy resource (DER) adoption and evolving load on the electric power distribution system. Distribution systems were originally designed to serve customer loads at low cost, not to serve more flexible (dispatchable or price-responsive) loads and generation such as DERs. However, in large quantities, new DERs could provide options for achieving national goals in decarbonization, resilience, energy equity, energy independence, and flexibility of energy supply.

Figure 1 shows how each U.S. Department of Energy (DOE) Energy Efficiency and Renewable Energy (EERE) office has an interest in DER, either as a means of interfacing their technology to the electric power system, or to support federal, state, and local government facilities. Without economies of scale, DER interconnections of renewable energy may cost more than bulk system interconnections, which are larger and at higher voltage levels than are typical of DERs. However, DERs could be well suited for massive, rapid deployment of renewable energy because their smaller sizes mitigate financial risk, require less supporting infrastructure, and shorten project schedules. Equally important, DER interconnections occur at the grid edge, where more communities and stakeholders can benefit. Some EERE technologies can only connect at the grid edge, including light-duty vehicle charging, residential solar, and most smart grid enabled buildings or campuses. To realize these opportunities, this report recommends that EERE and its constituent offices undertake a holistic research plan that enables valuation, analysis, and planning for large-scale DER adoption, in coordination with the Office of Electricity (OE), the Grid Modernization Laboratory Consortium (GMLC), and industry.

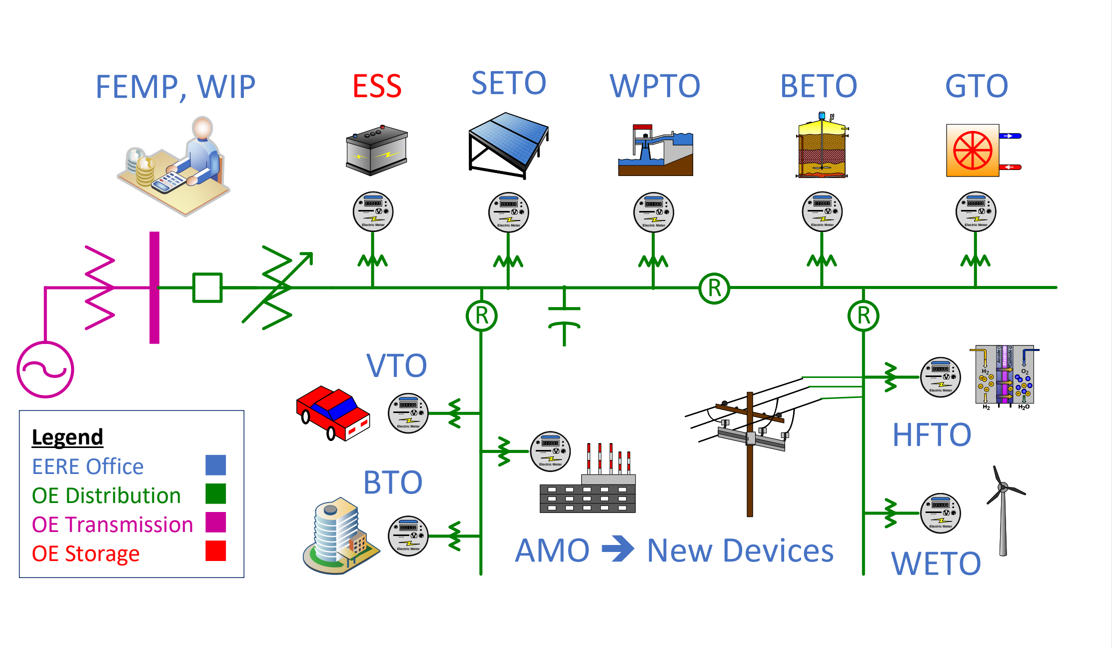

Figure 1. EERE technologies integrate with each other and with the bulk electric power system through distribution circuits that are bounded by meters at the grid edge, so planners may consider DER and grid options for expansion.[2]

---

[2] AMO is Advanced Manufacturing Office; BETO is Bioenergy Technologies Office; BTO is Building Technologies Office; ESS is Energy Storage Systems; FEMP is Federal Energy Management Program; GTO is Geothermal Technologies Office; HFTO is Hydrogen and Fuel Cell Technologies Office; SETO is Solar Energy Technologies Office;

Methodology

There were five steps in the approach; each is described in a numbered section of the report:

1. Gather EERE requirements for distribution system and DER modeling, and provide a working definition of DER. The power injection from DER can be bidirectional, with no fixed limit on size, voltage level, or geographic footprint. We focus on DER interconnections that are governed by Institute of Electrical and Electronics Engineers (IEEE) Standard 1547[3]. However, load control, which is not included in IEEE 1547, should be included with holistic DER analysis and is included in this report.

2. Gather open research questions on DER and distribution system integration challenges pertaining to voltage and frequency stability, variability, uncertainty, cybersecurity, physical security, fault protection, situational awareness, valuation of aggregate DER portfolios, alternative grid topologies, electrification of the economy, and energy equity. This information is organized from the researcher's viewpoint.

3. Organize the DER and distribution system analysis research questions into functional categories of regulatory, planning (i.e., device sizes and types), design (i.e., device settings and controls), operations, and the crosscutting analysis methods. This information is organized from the sponsor's and adopter's viewpoint.

4. Formulate a DER distribution system research roadmap that addresses the gaps apparent from comparison of the questions and functional needs with national-laboratory capabilities. Appendix A details more than 30 analytical tools, which reflects the strength of the laboratory system to develop such tools. These tools address different use cases; there is an opportunity to coordinate them more fully in holistic analyses.

5. Present an example set of next steps that EERE could follow to implement the roadmap.

Conclusions

The first conclusion of this study is that many capable tools and methods have been developed at the laboratories for DER modeling and analysis. These tools might be coordinated to analyze complete portfolios of DERs over the whole spectrum of grid integration concerns. This confirmed an initial premise of the project. Furthermore, the laboratories and their sponsors need more effective and faster ways of engaging with industry for technology transfer of tools and methods to the thousands of U.S. distribution utilities.

As a foundation to build upon, the GMLC's Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS) project has established a framework for multiple laboratories to collaborate in modeling and simulation. Where possible, the use of industry-wide interoperability standards in a research project would improve technology transfer. The Federal Energy Management Program (FEMP) and Weatherization and Intergovernmental Programs (WIP) offices, or their contractors, could benefit from holistic DER analysis tools that deliver better, more consistent results to their clients. Individuals or teams may follow their own best practices,

---

VTO is Vehicle Technologies Office; WETO is Wind Energy Technologies Office; WIP is Weatherization and Intergovernmental Programs; WPTO is Water Power Technologies Office.

[3] IEEE Standard 1547, *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*, Institute of Electrical and Electronics Engineers, Piscataway, New Jersey. Accessed May 11, 2021, at https://standards.ieee.org/standard/1547-2018.html

but a holistic framework could incorporate best-of-the-best practices. In meeting the requirements of FEMP and WIP, research project results should also become better suited for industry.

This report recommends a distribution system research roadmap to coordinate with ongoing projects at OE, especially in energy storage systems, microgrids, sensors, cybersecurity, and transactive energy markets. The roadmap should also coordinate with ongoing EERE projects, including the Building Technologies Office's Grid-interactive Efficient Buildings (GEB) initiative, the GMLC/Vehicle Technologies Office's Electric Vehicles at scale (EV@Scale) initiative, and the Hydrogen and Fuel Cell Technologies Office's H2@Scale initiative. The Solar and Wind Energy Technologies Offices just announced[4] a large grid-forming technology research consortium that should address some of the DER interconnection questions, but not the primary energy source dynamics of DER that will be critical to balancing load and generation.

This roadmap comprises several steps to fill the gaps. Many of these open research questions have been addressed before, but only for one DER technology in isolation, or from a single viewpoint, (e.g., the bulk system vs. the distribution system), or by using tools not widely adopted by other stakeholders. This roadmap aims to include the interactions between technologies and decision spaces, to achieve high adoption by industry, and to take greater advantage of other work. A common delivery platform, as described herein, will enable this.

As a final conclusion, most of these recommendations would be candidates for OE, GMLC, and/or industry work, but the prioritization may differ. OE and GMLC have broader responsibility for the grid, but they are agnostic to DERs except for distributed storage. EERE offices place a higher priority on reducing the barriers to energy efficiency and renewable energy integration, i.e., they are not agnostic to DER. Industry and regulatory sectors also have broader responsibility for the grid, and their acceptance will be essential if EERE-funded research under this roadmap is to have an impact. On the other hand, industry and regulatory bodies must work within existing financial and technical infrastructures. EERE-funded research can explore more options.

Roadmap Research Projects

The first set of targeted research projects, listed below, will yield short-term benefits, i.e., within a few years and with little regret if other energy sources outpace DER adoption. These are all conditioned on using the common delivery platform (described later) for technology transfer and replicability.

1. Evaluate new DER interconnection standards and grid integration pathways for large-scale DER deployment, including traditional load control. Utilities have been reluctant to accept communications-based or adaptive controls, even though such methods can mitigate DER impacts. EERE offices also need to achieve a shared awareness of DER interconnection practices.

2. Develop new distribution design practices that would be more compatible with massive DER deployment than radial feeders designed for uni-directional power flow. The most promising are upgrades to distribution feeder communications, protective relays, and voltage controls that could substantially increase the feeder's DER hosting capacity. Faulted circuit protection is a high priority in the short term because of the potential for loss of life and property damage that DER might cause and the importance attached to this risk by industry.

---

[4] *Solar Energy Technologies Office Fiscal Year 2021 Systems Integration and Hardware Incubator Funding Program*, U.S. Department of Energy. Accessed August 17, 2021, at https://www.energy.gov/eere/solar/solar-energy-technologies-office-fiscal-year-2021-systems-integration-and-hardware.

3. Develop new distribution grid planning methods and tools compatible with massive penetration of DERs. These tools should capture the uncertainty of DER adoption and operations and use DER deployments as non-wires alternatives in grid planning to achieve economic targets (investment deferral, loss reduction) and security targets (reliability, resilience).
4. Encourage FEMP and WIP to use the common delivery platform in their facility planning and upgrading projects. This practice would provide two-way benefits: better, more consistent results for the client facility than by following individual best practices, and feedback on usability of the research project results and the common delivery platform.
5. Include model-based design in future demonstrations and pilot projects. Demonstration project teams should use roadmap tools and models to size components and set control parameters, testing them before field deployment. The other project stakeholders can then evaluate the demonstration on a common set of metrics.
6. Develop new planning and regulatory practices that improve energy equity or deliver local community benefits. The first priorities are data collection, studies, and analyses that measure equity related to DER adoption and use. Then propose alternatives to existing practices that improve energy justice in access to DERs and their benefits.
7. Develop new practices that improve community resilience and reliability. These could be based on IEEE Standard 1366[5] reliability metrics for normal events, or on resilience metrics to be defined by the GMLC for extreme events. Microgrids may improve community resilience, if allowed by updated standards. New analysis tools are needed to assess the value of DERs and microgrids providing resilience and reliability to customers in extreme event scenarios.
8. Develop regulatory models and studies that capture how retail rates and utility programs affect the adoption and operation of DERs, and inform regulators on the resulting costs and benefits to the distribution system.
9. Develop control and aggregation architectures (and solvers) for large-scale DER microgrid coordination to provide capacity and ancillary grid services. For scenarios where DER displaces bulk power generation, microgrid or networked microgrid control architectures need to be developed for load balancing.
10. Develop solutions for hybrid power and communication networks to take advantage of rich data streams for integrated sensing and control of DERs. Advanced distribution management systems and distributed energy resource management systems (DERMS) need to incorporate these data streams with standards for DER communications, cybersecurity, and interoperability. The GMLC-funded projects GridAPPS-D™ and FAST-DERMS provide possible starting points. Holistic DER analysis needs to include the cost and benefit of enhanced controls and communications, which provide value beyond DER integration.

The second set of targeted research projects looks further ahead, i.e., they may take several years to yield benefits. They would become important if DERs outpace other energy sources. These projects can all use the common delivery platform.

1. Explore new grid architectures for massive deployment of DERs, especially urban secondary networks, converting radial feeders to meshed, fractal microgrids, and other distributed topologies. Medium-voltage DC grids provide another option for massive DER deployment. These

---

[5] IEEE Standard 1366, *Guide for Electric Power Distribution Reliability Indices*, Institute of Electrical and Electronics Engineers, Piscataway, New Jersey. Accessed May 11, 2021, at https://standards.ieee.org/project/1366.html.

grid architectures will be fit-for-purpose, migrating from the paradigm of radial and hierarchical load-serving circuits.

2. Evaluate multi-sector electrification of the economy, including buildings, transportation, and industry. This would make electricity even more important to the economy and social fabric, which in turn would call for even more reliability and resilience from the grid. It is still difficult in many regions to construct new extra-high-voltage transmission lines for bulk renewable integration. On the distribution system, it may be easier to increase operating voltage levels to connect more DERs. Infrastructure co-simulation work is in progress with HELICS and the North American Energy Resilience Model (NAERM) to support further analysis of electrification.

3. Develop a new framework for designing reliability metrics that recognize the reliability value of behind-the-meter DERs to customers and the system. This framework should go beyond current distribution reliability metrics focused on loss of load, and propose new performance metrics related to loss of service from DERs.

4. Encourage and participate in the development of a new mixed-integer optimization solver that is suitable for huge DER optimization problems. Commercial solvers are available, but they may not scale up as needed. A similar need exists for linear solvers that could scale up to much larger transient circuit models for inverters. The Office of Science and/or OE may also be interested in projects that build on recent DOE investments in massively parallel, heterogeneous compute clusters with graphics processing units (GPUs).

5. Develop or adapt an open-source tool for transient and harmonic analysis in research projects. Massive DER adoption may invalidate the continued use of positive-sequence dynamic simulation on the bulk system, leading to the need for more three-phase transient simulation on larger models. Commercial tools are available, but they are not flexible enough in model conversion, automation, and code customization. Those features will become more important in designing new controls and power electronic interfaces for DER.

Roadmap Delivery Platform

The roadmap includes an effective way to deliver research results, in particular the tools and models, to maximize their broader impact. We intend to avoid project deliverables that only satisfy the project statement of work, but never achieve widespread adoption outside of the originating laboratory or university. Therefore, we suggest a common delivery platform (Figure 2) to host all tools and models delivered by roadmap projects, with accompanying technology transfer activities. This step is foundational, and could begin first so that other projects take advantage of it. We recommend five common delivery platform elements:

1. For technology transfer, annual releases would occur with updates to documentation, examples, and training modules from completed projects. Associated with each platform release, a full-day or half-day workshop could be held in the Washington, DC, area with hands-on training and industry feedback sessions. The recorded training sessions and examples would be available on the internet year-round.

2. For technology transfer, EERE could consider funding platform ”office hours” and a web-based discussion forum. Developers and users of the platform, from both industry and academia, can then receive timely help in adopting it.

3. For holistic simulation studies, the platform would include a grid-interactive reference model implementation of each DER technology. These do not have to be best-of-breed models, but should be adequate for holistic portfolio studies, e.g., when a study focused on solar DER also needs to consider wind, buildings, and vehicles. The reference models also serve as examples for other research teams outside the national laboratories. Features need to include primary energy source dynamics, forecasting, response to grid voltage, and response to grid frequency. The most pressing needs are for grid-responsive building and vehicle models, but each EERE technology office should have a reference model for holistic DER studies.

4. For ease of adoption, common data formats should be identified from national and international standards, where they exist. Examples include the International Electrotechnical Commission's Common Information Model (CIM) for electric power systems, and the IEEE Standard 1547 parameters for DER. A research team can usually adapt or develop more efficient, flexible, and convenient data formats in each project, but individually customized formats later become a barrier to industry adoption.

5. For ease of adoption, the platform should include an application program interface (API) that supports tool scripting, simulation process steps, iterative solution, and data file management. For use cases that require co-simulation, HELICS should be used for messaging in the API, and HELICS should be enhanced to provide better speed and convergence for the larger bidirectional (or nonhierarchical) energy transfers that may come with massive DER deployments. The delivery platform's other API requirements go beyond HELICS. Conversely, if a use case does not need co-simulation, then it does not need HELICS.

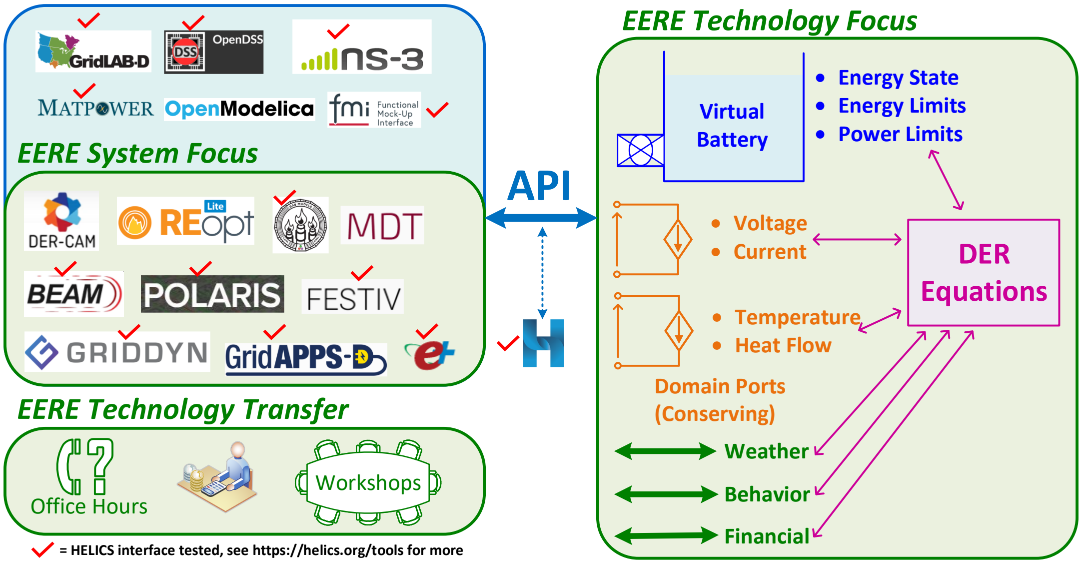

Figure 2. The common delivery platform includes a reference implementation of each DER technology with a new application program interface (API) and continuing technology transfer.

Reviewers of this roadmap have stated that research-grade tools are often not widely adopted, and that industry partners do not always know how to follow up from a research project. The common delivery platform would provide some ongoing support of tools after the development funding ends. In addition, EERE may consider the following actions:

1. Fund a year of follow-up engagement with industry partners, instead of terminating projects immediately after meeting the research goals.
2. Prefer the release of software tools with open-source license terms that are amenable to commercialization, e.g., the Berkeley Software Distribution (BSD) license instead of the GNU General Public License (GPL).
3. Fund multiyear research consortia where possible, because they provide ways for multiple industry partners to stay engaged.
4. Participate in a higher-level, strategic reimagining of how DOE and the national laboratories ought to engage with industry, while respecting the boundaries of the Electric Power Research Institute (EPRI), the National Rural Electric Cooperative Association (NRECA), etc.

More details on each step of the roadmap can be found in the report's main body. The scope of this report was limited to modeling and analysis capabilities. Hardware development, systems engineering, policy changes, and field demonstrations were out of scope, except for the recognition that modeling and analysis capability informs or enables them all.

Acronyms and Abbreviations

AC	alternating current
ADMS	advanced distribution management system
ADN	active distribution network
AGM	Advanced Grid Modeling
AGRD	Advanced Grid Research and Development
AMI	advanced metering infrastructure
AMO	Advanced Manufacturing Office
ANL	Argonne National Laboratory
API	application program interface
BAU	business as usual
BETO	Bioenergy Technologies Office of DOE
BSD	Berkeley software distribution
BTM	behind the meter
BTO	Building Technologies Office
CAM	customer adoption model
CESER	Cybersecurity, Energy Security, and Emergency Response
CHP	combined heat and power
CIM	Common Information Model
CPP	critical peak pricing
CVR	conservation voltage reduction
DER	distributed energy resource
DERMS	distributed energy resource management system
dGen	Distributed Market Generation Demand
DISCO	Distribution System Integration Cost Options
DLL	dynamic link library
DNP3	Distributed Network Protocol version 3, now IEEE Standard 1815
DOE	U.S. Department of Energy
DN	distribution network
DR	demand response
DSO	distribution system operator
EERE	Energy Efficiency and Renewable Energy
EIOC	Electricity Infrastructure Operations Center
EMeRGE	Emerging technologies Management and Risk evaluation on distribution Grids Evolution
EMT	electromagnetic transient
EPRI	Electric Power Research Institute
ES	energy storage
ESGC	Energy Storage Grand Challenge
ESIF	Energy Systems Integration Facility
EV	electric vehicle
EVI-Pro	Electric Vehicle Infrastructure Projection Tool

FAST-DERMS	Federated Architecture for Secure and Transactive Distributed Energy Management Solutions
FEMP	Federal Energy Management Program
FNCS	Framework for Network Co-Simulation
GEB	Building Technologies Office's Grid-interactive Efficient Buildings initiative
GMLC	Grid Modernization Laboratory Consortium
GNU	GNU's not Unix, a self-referential acronym
GPL	GNU General Public License
GTO	Geothermal Technologies Office
HELICS	Hierarchical Engine for Large-scale Infrastructure Co-Simulation
HEMS	home energy management system
HFTO	Hydrogen and Fuel Cell Technologies Office
HILP	high impact, low probability
HTE	high-temperature electrolysis
HVAC	heating, ventilating, and air conditioning
ICE	Interruption Cost Estimate
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IMT	Integrated Modeling Tool
KLU	a sequential linear matrix solver for electric circuit equations
LBNL	Lawrence Berkeley National Laboratory
LDE	low-cost, dispatch-constrained electricity
LTC	load tap changer
LTE	low-temperature electrolysis
MATPOWER	an open-source power flow and optimization tool by MathWorks
MDT	Microgrid Design Toolkit by Sandia National Laboratories
METIS	a set of programs that partitions matrix equations for parallel solution
MILP	mixed-integer linear programming, for optimization
MILQ	mixed-integer quadratic programming, for optimization
MIRACL	Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad
MMT	million metric ton
MOST	MATPOWER Optimal Scheduling Tool, now part of MATPOWER
MVA	megavolt-ampere(s)
NASEO	National Association of State Energy Officials
NARUC	National Association of Regulatory Utility Commissioners
NREL	National Renewable Energy Laboratory
ns-3	network simulator, version 3
NWP	network protector
OCHRE	Object-oriented Controllable High-resolution Residential Energy (model)
OE	Office of Electricity
OpenDSS	Open Distribution System Simulator
OpenFMB	Open Field Message Bus

OPF	optimal power flow
OT	operational technology
PEI	power electronic interface
PEV	plug-in electric vehicle
PHIL	power hardware in the loop
PNNL	Pacific Northwest National Laboratory
PQ	real and reactive power
PRECISE	PREconfiguring and Controlling Inverter SEt-points
PSPS	public safety power shutoff
PUC	public utility commission
PV	photovoltaic
PyDSS	Python interface for OpenDSS
RD&D	research, development, and demonstration
ReEDS	Regional Energy Deployment System
REPAIR	Risk-controlled Expansion PlAnning with dIstributed Resources
RT-OPF	real-time optimal power flow
SA	DOE's Strategic Analysis Team, successor to SPIA
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SAM	System Advisor Model
Sandia	Sandia National Laboratories
SCADA	supervisory control and data acquisition
SETO	Solar Energy Technologies Office (DOE)
SLAC	Stanford Linear Accelerator Laboratory
SMR	steam methane reforming
SPIA	Strategic Priorities and Impact Analysis, now Strategic Analysis (DOE)
TCP/IP	Transmission Control Protocol/Internet Protocol
TEMPO	Transportation Energy & Mobility Pathway Options^{TM}
TOU	time of use (rates)
TSO	transmission system operator
UC	unit commitment
VTO	Vehicle Technologies Office (DOE)
WETO	Wind Energy Technologies Office
WIP	Weatherization and Intergovernmental Programs
WPTO	Water Power Technologies Office

Acknowledgments

This material is based on work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Strategic Priorities and Impact Analysis (SPIA) Agreement Number 37012. During the project, SPIA became the Strategic Analysis (SA) Team in an EERE reorganization.

The project team would like to thank our panel of external reviewers from Argonne National Laboratory, the Electric Power Research Institute, the National Rural Electric Cooperative Association, and Oak Ridge National Laboratory for valuable comments as the project neared completion.

Contents

Figures

Tables

1.0 Distribution System Technical Challenges

This project was undertaken to categorize and summarize the technical challenges arising from increased distributed energy resource (DER) adoption and evolving load on the distribution system. In the planning stages, the Strategic Priorities and Impact Analysis Team (SPIA/SA) of the Office of Energy Efficiency and Renewable Energy (EERE) identified five high-level needs:

- Build on existing work within EERE and across other U.S. Department of Energy (DOE) offices.
- Analyze multi-technology portfolios for the value, impact, security, and resilience of DERs.
- Coordinate high-resolution and bulk-scale models of DERs.
- Develop new fundamental grid architecture options for high penetrations of DERs.
- Better understand the needs of decision makers who are evaluating DERs.

See Appendix B for more details of the preliminary survey. This first section of the report presents a working definition of DER and the interests of different EERE offices in DER. Section 2.0 formulates the research questions in more detail, and Section 3.0 identifies the existing capabilities of national laboratories to answer those questions. In Section 4.0, we summarize the gaps and present a research roadmap to fill those gaps. In Section 5.0, we present an example set of steps to implement the roadmap.

1.1 Types of DER, Devices, and Equipment

DER is a broad term that can encompass resources with generation, consumption, and storage characteristics; see Table 1 for some example definitions. The resources are distributed, are not connected to the bulk system, are usually of smaller scale than bulk devices, and can be front-of-meter or behind-the-meter (BTM) devices. In this report, DER is generally classified as DER generation, DER storage, and demand-side resources. DERs span multiple technologies that are associated with diverse offices under EERE, see Table 2. All are connected to the distribution network. They can look like either load or generation, but are able to control their power demand or supply, as shown in Figure 3. The wide-scale adoptions of diverse DERs should be studied in tandem to understand the effects of not just siloed integration of single technologies, but the multitude of DERs that are being integrated onto the network.

Earlier versions of Institute of Electrical and Electronics Engineers (IEEE) Standard 1547 [1] applied to DER up to 10 MVA in size, and many took this as part of the DER definition. However, IEEE 1547-2018 has no quantitative bounds on the definition of DER, whether based on MVA size, voltage level, or geographic dispersion. Within the standard, DER is “not directly connected to a bulk power system” while the bulk power system includes “any electric generation resources” without regard to size or voltage. After much deliberation, the IEEE P1547 working group and ballot pool were unable to agree on a more precise definition of DER. Similarly, a DER task force working on the International Electrotechnical Commission’s (IEC’s) Common Information Model (CIM) concluded that DER is not precisely defined and may eventually become a legacy term. Definitions of DER by several organizations are shown in Table 1. In the United States, a working definition of DER might be a resource for which the utility, or the regulatory authority, applies the requirements from IEEE 1547.

Table 1. Definitions of Distributed Energy Resources

Definition	Source
A Distributed Energy Resource (DER) is any resource on the distribution system that produces electricity and is not otherwise included in the formal NERC definition of the Bulk Electric System (BES)	NERC[a]
Distributed energy resources are small, modular, energy generation and storage technologies that provide electric capacity or energy where you need it.	NREL[b]
[Distributed Energy Resources (DER) are] technology advancements in connected loads, solar photovoltaics (PV) and energy storage.	EPRI[c]
DER as used in this report includes distributed generation, distributed energy storage, energy efficiency, demand response and electric vehicles.	PNNL[d]

(a) North American Electric Reliability Corporation
(b) National Renewable Energy Laboratory
(c) Electric Power Research Institute
(d) Pacific Northwest National Laboratory

1.1.1 DER Generation

DER generation covers multiple technologies, including those from renewable energy sources. The DER generation source with the most capacity integration to date has been solar photovoltaic (PV). Motivated by falling solar generation prices and evolving rate structures, there has been widespread adoption of PV. Other renewable DERs include those from wind and water, with small-scale run-of-river being well established as a technology, but potential wave and tidal DERs not yet having a clear technology forerunner or paradigm. Biomass and waste-to-energy are increasingly being coupled with agriculture by-products and municipal waste systems, respectively. Electrochemical DER generation includes fuel cells and electrolyzers, although these also have energy-storage and energy-consumption (for hydrogen production) properties that can give these technologies DER storage and demand-side characteristics. Nonrenewable DERs include small-scale fossil-fired generation and cogeneration for heat and electricity production, such as combined heat and power (CHP) generation.

Many of the DERs described here have power electronic interfaces (PEIs) to the grid and are inverter-based. Legacy inverters were programmed to trip in response to a fault or disturbance on the grid with negligible effect. However, at higher penetrations of inverter-based DER, the tripping leads to a significant portion of the generation going offline, thus exacerbating the instability of the grid under fault. This was seen in the Canyon fire event [2] and the Blue Cut fire event [3]. Though most of the generation lost in the two fire events was connected to the bulk system, the ride-through capability is becoming increasingly important for the distribution-connected, inverter-based DERs. Output from some DERs, such as PV, can be highly variable when deployed without storage. This increases switching operations and wear on the load tap changers and voltage regulators that maintain voltage within operating limits. Moreover, at higher penetrations, overvoltages occur along the feeders in the periods of peak

Table 2. Descriptions of DER Technologies of Interest to EERE Offices

Technology	Description	Office
Combined Heat and Power	Cogeneration of concurrent production and use of heat and electricity generation from a single source of energy located near the point of consumption.	BETO
Demand-Side Aggregators	Aggregation of demand-side resources (e.g., customer loads, DERs) to provide customer and grid services through coordinated control (distributed or centralized).	BTO
Grid-Interactive Efficient Buildings (GEB)	Next generation energy efficient buildings with sensors, controls, connectivity and communication that enable provision of grid-services.	BTO
Responsive Loads	Closely related to GEB, with focus on components like controlled lighting and thermostatically controlled load (TCL). “Demand response” may refer to the peak shaving aspect.	BTO
Thermal Energy Storage	Thermal energy storage (e.g., electric storage heaters, building thermal mass) is a diverse range of energy storage solutions using BTM resources that can shift demand.	BTO
Flow Battery	Flow batteries (e.g., redox flow battery systems) are scalable and provide a long-duration (hours to days) energy storage solution.	HFTO
Fuel Cells	Fuel cells and electrolyzers can be used at the grid-edge as generation or energy storage, respectively, to help integrate renewable generation.	HFTO
Li-ion Battery Storage	Li-ion battery storage technologies are being used in BTM and larger-scale distribution applications to provide grid services.	HFTO
Solar Photovoltaic	Solar photovoltaic DER provides electricity, differentiated from utility-scale PV by proximity to end-use and the point of interconnection.	SETO
Solar Thermal	Solar thermal can offset electricity consumption (e.g., for water heating) or provide complementary storage for electricity generation.	SETO
Electric Vehicles (EV)	Electric vehicles include battery EVs, plug-in hybrid EVs, and fuel cell EVs.	VTO
EV Charging Infrastructure	Infrastructure required to charge battery and plug-in hybrid EVs, including level 1 (120 V AC), level 2 (240 V residential or 208 V commercial AC), or DC fast charging.	VTO
Distributed Wind Power	Distributed wind provides electricity, differentiated from utility-scale wind by its point of interconnection.	WETO
Run-of-river Hydro	Hydroelectric generation, which can be intermittent without storage or pondage. Differentiated from utility-scale hydro by its proximity to end use and the point of interconnection.	WPTO
Wave Energy Converters	Conversion of kinetic and potential energy from waves to mechanical or electrical energy; may be grid-edge devices.	WPTO

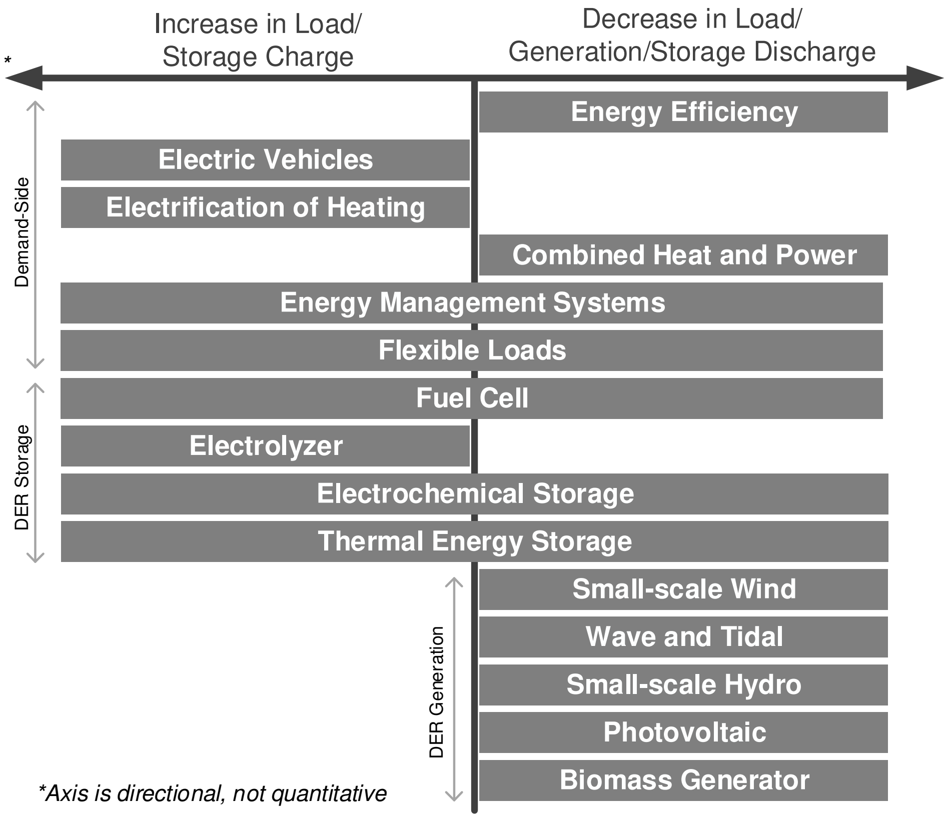

Figure 3. DER may control its generation, load, or both, depending on its type

DER generation and low demand. Hence, development of advanced inverter functionality is needed to provide grid support functions such as voltage/frequency ride-throughs and volt/var and volt/watt support. These advanced interconnection practices are recommended in IEEE 1547-2018 [1] and required by California and Hawaii through Rule 21 [4] and Rule 14H [5], respectively. Still, most of the inverters connected to the grid follow legacy practices. Thus, reprogramming the legacy inverters or replacing them with advanced inverters remains a significant challenge.

DER generation resources may be co-located to complement the intermittent nature of individual DERs. One such configuration is hybrid wind-PV systems, in which PV and wind might work better together than separately. Developing optimal hybrid configurations and associated integrated controls (e.g., volt/var) remains a challenge, as do the controls to provide grid services from hybrid systems.

1.1.2 DER Storage

Energy storage systems are also being deployed in a distributed manner. DER storage includes electrochemical storage technologies such as lithium-ion and flow battery technologies, among others. Thermal energy storage is another option that can be used both to shift demand, if heat is an end-use, and/or to be converted back to electricity. Hybrid energy storage systems are also being deployed to combine cost and performance characteristics of different storage technologies. Moreover, DER storage is often deployed with DER generation to cope with the inherent variability of resources like wind and PV.

1.1.3 Demand-Side Resources

Demand-side resources are emerging as a potential source of flexibility. These include grid-interactive efficient buildings (GEBs) and demand response. These can be classified residential, commercial, and industrial load classes. Energy-efficient buildings are increasingly considered the main resource for demand-side management as they participate in energy efficiency and peak-shifting programs run by utilities. For large commercial or residential buildings, electric heating and cooling represent a significant load that can be optimally controlled to reduce operating costs and achieve network benefits. Similarly, thermal storage resources (i.e., heating or cooling via thermal storage) can provide flexibility by increasing demand when needed to avoid the curtailment of DER generation.

Heat pumps coupled with thermal energy storage systems can also participate in demand response programs. Although PV systems are mainly considered part of DER generation, they can provide demand-side functions such as peak shaving. Other flexible loads that may provide demand-side services include electric vehicles (EVs), power electronic loads, and water heaters.

1.2 Technology Office Focus

The various EERE offices and the Office of Electricity (OE) may have different levels of interest in DERs, and emphasize different aspects of DER. Each office has an interest in the distribution system as well, either by directly connecting their technology to the distribution grid (Figure 4) or as a planner (Figure 5). This part of the report summarizes, compares, and contrasts those points of view to help make sure that no EERE questions are missed. It also helps identify some common elements that should provide opportunities for collaboration.

1.2.1 Energy Efficiency

Advanced Manufacturing Office (AMO): The AMO develops manufacturing processes and materials to improve U.S. competitiveness in EERE technologies. For example, AMO participates in the Energy Storage Grand Challenge (ESGC) [6]. It is important that new product developments for the grid have a path to industry adoption.

The AMO also seeks to improve energy efficiency of the industrial sector. Deploying CHP with other BTM resources could help meet these efficiency goals. If the facility can export power, these resources could be integrated with the distribution system as DERs to provide additional value. Medium-voltage distribution system connections can also provide more efficient electrified manufacturing and DER systems.

Building Technologies Office (BTO): High-fidelity, community-scale modeling is needed to capture interactions between energy-efficient and grid-interactive buildings on the distribution network. BTO's GEB initiative focuses on making equipment more intelligent through use of next-generation sensors, controls, connectivity, and communications. These enhanced capabilities can deliver comfort while harvesting energy from buildings, which can reduce energy costs, support grid reliability and resilience, defer network upgrades, and help balance the supply of renewable energy.

Demand-side management (DSM) schemes can deliver significant grid benefits. The design of retail tariff schemes, e.g., time-of-use (TOU) pricing, critical-peak pricing (CPP), net energy metering, demand charges, day-ahead pricing, and real-time pricing, drive the adoption of BTM DERs such as solar PV and battery energy storage systems. Transformative market designs, such as transactive energy markets, possibly incorporating blockchain, will also change the adoption, use, and dispatch of customer DER assets.

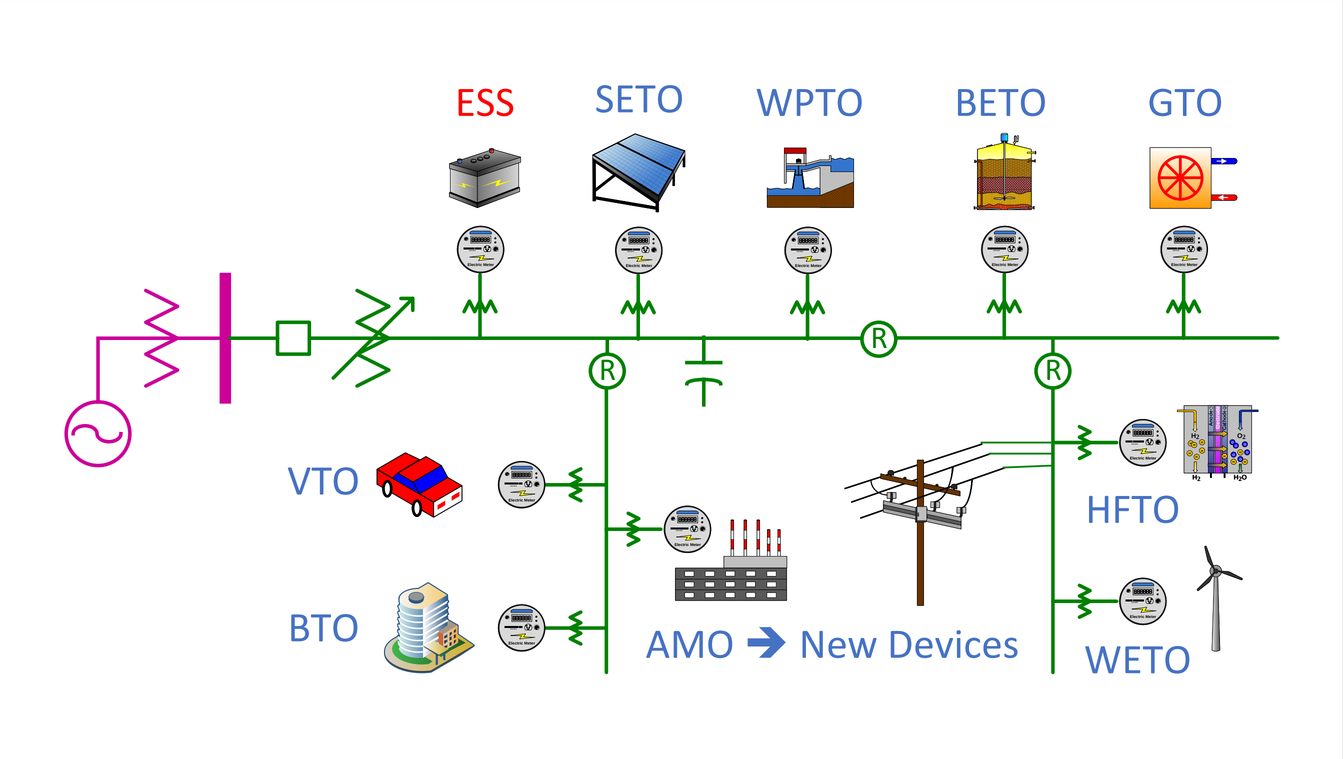

Figure 4. EERE technologies integrate with each other and the bulk system through distribution circuits bounded by meters.

Emerging demand-side technologies affect load composition, consumption profiles, and electrical characteristics of loads. These can introduce new consumption patterns (e.g., the electrification of transportation and heating) that change load profiles. These can also affect the voltage and frequency dependence of loads (e.g., power electronic loads and energy-efficient lighting), with effects on traditional utility voltage control strategies such as conservation voltage reduction (CVR).

To share value between building and grid owners, all BTM assets must be considered in grid interactions. This includes vehicle charging and DERs. Up to 30% of the building load should be responsive load, whether by direct load control or transactive energy mechanisms. However, these goals also need to account for equity and resilience.

Federal Energy Management Program (FEMP): The FEMP is concerned with energy efficiency and resilience in federally owned buildings and campuses, excluding military facilities. FEMP is involved in procurement, contracting with energy service companies, loan guarantees, and metering to help federal facilities meet these goals. Projects include long-term electric service improvements, microgrids, and net-zero campuses. FEMP arranges for technical assistance from national laboratories and other contractors. NREL's Renewable Energy Integration and Optimization (REopt) has been used for some planning studies with DERs.

Weatherization and Intergovernmental Programs (WIP): The WIP office provides income-qualified home weatherization assistance to individuals, and technical assistance to state and local governments, for improving energy security and affordability. The government WIP recipients may benefit from better ways to integrate DERs with the grid. Conversely, the other EERE offices may benefit from WIP data and processes to improve equity.

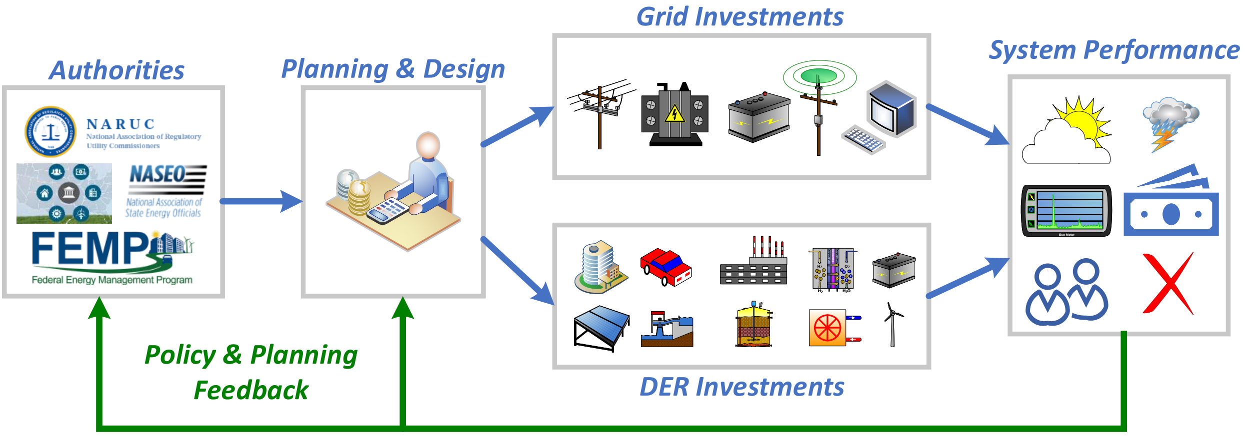

Figure 5. Regulators, along with FEMP and WIP, authorize planning with DER and grid components.

1.2.2 Renewable Power

Solar Energy Technologies Office (SETO): About 40% of SETO's research budget has supported system integration and soft costs, reflecting importance of that work in the overall cost of solar power. Variability, uncertainty, forecasting, communication, control, reliability, and cybersecurity might seem to be issues for the grid, but they can also present barriers to solar integration. The office has been supporting interconnection standards IEEE 1547, 2030, and 2800 [7]. With increasing adoption of smart inverters, communication, control, and cybersecurity are potential barriers to integration of solar DERs. Overall, utility-scale solar is about 60% of total U.S. solar capacity [8]. Distributed solar is the other 40% of U.S. solar capacity, which means there will be millions of smart inverters deployed. In some states, distributed solar is more significant than in the country at large, so the ability to forecast adoption rates would help utility planners. The office has been interested in grid-forming inverters, solar+storage (thermal and electrical), microgrid operation, resilience, and BTM integration as ways to enhance the value of solar power. Improvements to solar panel and inverter reliability would improve the economics of solar.

Wind Energy Technologies Office (WETO): In recent years, this office has emphasized bulk system interconnections, especially offshore wind. There is still interest in coordinating real and reactive power (PQ) control on distribution circuits and medium-voltage collection circuits, providing ancillary services, and coordinating protection with low-voltage ride-through on distribution systems. Grid-forming technologies are essential for wind to provide black-start capability to either the bulk system or microgrids. Hybrid wind-battery DERs may increase, and arctic wind-diesel systems are still important in Alaska. For the latter, WETO might be interested in replacing or augmenting the diesel component.

Water Power Technologies Office (WPTO): As part of its Powering the Blue Economy initiative [9], WPTO is considering grid-edge integration of small-scale hydro (e.g., run of river) and wave energy harvesting devices that produce large variation in power output. WPTO is also considering how the existing fleet of small-scale hydro DERs could be maintained and connected to the grid. Distributed pumped storage would be a new type of storage DER to complement battery energy storage systems. New water-power DERs encounter the same

DER interconnection process as wind and solar DERs, so there is an opportunity for WPTO to build on prior work by WETO and SETO on interconnections.

Geothermal Technologies Office (GTO): The advent of enhanced geothermal systems has created opportunities for using geothermal energy away from naturally occurring sources. Community geothermal plants and building-scale geothermal plants, already used in Iceland, may become viable DERs in the United States. Establishing power purchase agreements has been of recent concern.

1.2.3 Sustainable Transportation

Vehicle Technologies Office (VTO): The VTO supports development of plug-in electric vehicles (PEVs), which constitute DERs that absorb and generate electric power at different times. The charging demand could be up to 1.5 MW for medium-duty vehicles and heavy-duty vehicles (e.g., transit buses and heavy trucking). The grid impact analysis needs to consider capacity, charging coordination, and demand forecasting. Vehicle-to-grid (V2G) operation may allow PEVs to provide ancillary services, but the effect on battery performance must be accounted for.

The office also researches energy-efficient mobility systems, which influence the use of PEVs. The grid may see each PEV as a variable DER, but in reality they are mobile and time-varying DER. Simulations of traffic patterns and driver behavior may provide better forecasts for grid planning and operation.

In parallel with PEV research, VTO also develops advanced combustion systems and fuels. Advances in these areas would influence the adoption rates of PEVs. One of the new transportation fuels could be hydrogen, which would also affect the grid when produced in much larger amounts than it is now.

Hydrogen and Fuel Cell Technologies Office (HFTO): HFTO focuses on hydrogen fuel production and hydrogen fuel cells, which can be connected as DERs. Fuel cells may also be integrated with solar DERs on the distribution network, or in microgrids.

There is even more potential for HFTO's H2@Scale initiative [10] to use more electricity. The U.S. currently makes 10 million metric tons (MMT) of H_2 per year from natural-gas steam-methane reforming (SMR). One H2@Scale goal is to produce that much from other sources, including high-temperature electrolysis (HTE) from nuclear plants, and low-temperature electrolysis (LTE) from low-cost, dispatch-constrained electricity (LDE), where the LDE is wind, solar, geothermal, or any other variable renewable energy [11]. In both LTE and HTE, the ability to store H_2 lets each generator run without curtailment. If successful, H2@Scale could go far beyond 10 MMT per year to decarbonize both the transportation and industrial sectors [12]. Some of the H_2 production could come from DERs, especially if it uses less water than larger-scale, higher-temperature plants.

Flow batteries are closely related to fuel cells. The most recent funding opportunity in flow batteries was sponsored by AMO and OE [13].

Bioenergy Technologies Office (BETO): Biowaste can be used to produce electricity by direct combustion, or by burning the gas created from anaerobic digestion, e.g., landfill gas DER. Microbial fuel cells are not yet large enough for DER applications. Interest is stronger in using the biomass to make fuels.

1.2.4 Office of Electricity Perspective

OE comprises an Advanced Grid Research and Development (AGRD) activity and four power marketing administrations (PMAs) that operate and market federal hydroelectric generation. Within AGRD, there are two groups:

- Grid Communications and Control, including transactive systems, distributed applications, new sensors, and advanced grid modeling (AGM)
- Grid Systems and Components, including storage, transformer resilience, and power electronics.

OE's work on storage, transactive systems, distributed applications, sensors, and microgrids would be of special interest for a roadmap for distribution system and DER research. The Grid Modernization Laboratory Consortium (GMLC) Grid Architecture work [14] applies control theory, network theory, and laminar coordination principles to create new fundamental grid architectures that could be appropriate for high penetrations of DERs, along with other technologies and objectives such as advanced sensors, distributed control, resilience, microgrids, and modularity. An architecture provides a vision for the complete system; communications, sensing, control, and coordinating frameworks are needed, along with the individual technologies.

OE funded the development of GridLAB-D software^{TM} [15] and continues to sponsor new features, particularly unbalanced dynamic simulation for microgrids, and distributed applications. For the past few years, distribution system research programs have needed to show effects on the bulk power system for justification.

OE has other projects on advanced grid modernization and resilience with specific areas related to distribution analysis:

- Advanced Distribution Management System Test Bed: This includes a realistic system model and power hardware in the loop (PHIL) to evaluate advanced distribution management system (ADMS) applications.
- Federated Architecture for Secure and Transactive Distributed Energy Management Solutions (FAST-DERMS): This GMLC project is developing a DER aggregation architecture for both utilities and industry to provide system services from groups of diverse DERs participating in the market.
- Transactive Energy: The GridWise Architecture Council defines transactive energy as a means of controlling generation, consumption, or flow of electric power using economic or market constructs, while considering grid reliability constraints. OE has projects in theory, tools, and demonstrations of transactive energy. The Distribution System Operations Transactive Energy (DSO+T) study is evaluating transactive energy on a regional scale, with a geographic setting in Texas.
- Microgrids: Puerto Rico resilience work included some distribution network modeling with IEEE 1547 advanced inverter functions. Microgrid models and solution methods have been added to GridLAB-D.
- North American Energy Resilience Model (NAERM): This project considers the effects of distribution networks on bulk system reliability.
- Energy Storage Grand Challenge (ESGC): This initiative may have a distribution network integration element for BTM storage. High level use cases of ESGC include serving remote communities, critical services, facility flexibility, efficiency, and value enhancement, and electrified mobility.
- Renewable Electricity Futures Study: This was completed in 2012. Residential rooftop PV has been adopted much faster than the study assumed, because the cost has decreased by around 50% since then, with even larger decreases for utility- and commercial-scale PV.

1.3 Crosscutting Focus

This section describes some of the broader issues that are common to all technologies. One example is the need for grid modernization, so the section ends with a description of the GMLC.

1.3.1 Resilience and Cybersecurity

High-impact extreme events are increasingly affecting grid resilience. Resilience is defined as the ability of the grid to prepare for and adapt to changing conditions and to withstand and recover rapidly from disruptions, including deliberate attacks, accidents, and naturally occurring threats or incidents [16]. Natural disasters may include earthquakes, wildfires, volcanic eruptions, hurricanes, and snowstorms. The human-induced events may include deliberate sabotage, operator error, and cyberattacks. These extreme events usually cause large-scale outages, destruction of network assets, and public safety power shutoffs (PSPS) to prevent worse effects, e.g., risk of wildfire ignitions in extreme heat and high wind conditions.

Approaches are needed for enabling resilience through temporary alternative, operational, and emerging technology for distribution systems. The control and coordination of DERs has been hailed as a promising solution to support resilient grids. DERs may be deployed in microgrids in addition to their conventional stand-alone operation. Microgrids are small networks with a collection of electricity loads and generators that may be connected to a large-scale power system, but are able to operate independently of it. The formation of microgrids during an outage provides customers with more reliability and resilience of supply than that provided by a main grid connection alone.

There are no widely accepted quantitative metrics for measuring grid resilience, which remains a significant challenge in this area. Without measuring the current state of resilience and the incremental resilience that may be added by measures such as network upgrades, it becomes extremely challenging to attract new investment from the stakeholders. The GMLC metric team recently presented a roadmap for defining quantitative resilience metrics [17]. The metrics attempt to measure the current state of resilience and the effect of network investments on resilience. However, standardization and wide adoption of such metrics remain a challenge.

There is a concern that DER may increase the cyberattack surface of the distribution system. If an attacker were able to suddenly curtail DER output over a large region, the effect could be similar to sudden loss of several bulk generating plants. Widespread DER tripping has been triggered by non-cyber events, e.g., wildfires in California [2, 3] and the 2003 Italian blackout exacerbated by DER underfrequency tripping [18].

A successful cyberattack on DERs would have the same effect on the grid. Similarly, cyberattackers could manipulate loads to cause disturbances and outages on the grid. A known example of this occurred in Ukraine [19]. Cybersecurity is a crosscutting challenge for all types of DERs, because the vulnerability comes from exposed controls and communications, regardless of the energy production or end-use technology.

End-use loads on the distribution system have not been exposed to cyberattack until the advent of home energy management systems (HEMS) and smart metering. Residential-scale DER had also not been exposed to cyberattack until the advent of smart inverters with communications and control functions. Customers and third parties often have physical access to these more intelligent devices.

In contrast, the larger industrial and commercial loads and resources had more control capability, which increased the possible effects of cyberattack. With fewer locations, physical access may be easier to manage and mitigations easier to deploy. Adoption of more residential DERs will increase the challenge because of these factors:

1. There will be many more locations to protect.
2. Customers have different capabilities to manage cybersecurity.
3. Vendors have different capabilities to manage cybersecurity.

Much of the work on cybersecurity for DERs has focused on the adoption of general best practices from information technology. Examples include patch control, supply chain security, role-based access, and others. While important, there is little difference among these practices when applied to DER compared to other businesses. The operational technology (OT) is different with DERs, and OT cybersecurity for DER is still a unique challenge.

There are no accepted quantitative metrics for the cybersecurity performance of a grid with DERs. This poses a challenge to planning, design, and evaluation. If the accepted criterion is "zero failure," then unlimited cost of mitigation would be justified. However, perfection could never be reached. In other aspects of grid planning, quantitative measures like loss-of-load probability and mean time between failures are used to plan for rare events. Other measures like System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) are used to plan for more common events. None of these metrics are perfect, but they do provide a common basis for planning, design, and evaluation. DOE has developed the Interruption Cost Estimate (ICE) Calculator to assist in planning reliability improvements. Developing useful and accepted cybersecurity performance metrics for DER poses a new challenge.

OE's portfolio of research, development, and demonstration (RD&D) is focused on developing game-changing technologies that help utilities (1) secure today's energy infrastructure from advanced cyber and physical threats, and (2) design next-generation systems that are built from the start to automatically detect, reject, and withstand cyber incidents, regardless of the threat [20]. DOE conducts innovative RD&D to develop trustworthy, self-defending systems in the context of an increasing attack surface. Some of the key challenges OE's RD&D portfolio addresses are:

- developing cybersecurity tools and technologies that do not impede energy delivery functions
- ensuring proper operation of systems with diverse legacy and modern devices
- ensuring interoperability from diverse vendors and third-party providers
- anticipating security in the future grid
- strengthening energy sector security and resilience

Currently, within DOE, these challenges are being addressed by a dedicated office, the Office of Cybersecurity, Energy Security, and Emergency Response (CESER). CESER employs cutting-edge tools and technologies from artificial intelligence and quantum computing to develop algorithms and technologies that meet the evolving cyber- and physical security challenges outlined above. The office greatly values RD&D partnerships between the national laboratories, academia, the utility sector, and vendors. The goal is to secure energy infrastructure against all hazards—manmade or physical.

1.3.2 Bulk System Effects

Integration of DERs into the distribution system creates several challenges for the bulk system. Some of them are listed here:

- Bulk system protection: The uncertainty and variability associated with DER output has raised concerns over bulk system protective relaying. In particular, most of the DERs have PEI couplings with the grid rather than the electromechanical coupling of the synchronous generators. Hence, PEIs are required to be programmed to respond to changes in the bulk system, whereas synchronous generators can respond autonomously—i.e., the inertial response. This limits DER integration in low-inertia grids. Moreover, the PEIs are also limited by their overcurrent capability, since most of them can only provide 20% current over their rated values while traditional generators can supply up to six times their rated current [21]. This PEI current may not be high enough to operate power system relays during faults.

- Stability under fault conditions: In response to frequency or voltage disturbances, DERs with PEI cease to energize or may even trip. During momentary cessation, DER output is forced to zero for the duration of the disturbance, with a rapid recovery when voltage or frequency returns to the defined range. However, in a trip, there is no immediate return to service. Both practices can cause bulk system instability under a fault since a significant portion of the generation is taken offline, resulting in a further imbalance of generation and load.

- DER aggregation and visibility across transmission system operator/distribution system operator (TSO/DSO) boundaries: In a traditional interaction between DSO and TSO, the DSO shares forecasted (and real-time) power needs with the TSO who supplies the power. This minimal interaction becomes a limitation as increasing renewable DER penetrations on the distribution system makes forecasting demand difficult. Moreover, a TSO usually has no information about DERs in the distribution system. Without aggregation or visibility of generation assets across the TSO/DSO boundary, scheduling the operation of traditional generators is difficult. Such uncoordinated operation may result in shortages or surpluses of power. With DERs, existing communication and control infrastructure between TSOs and DSOs is a significant barrier in addition to conventional operating practices.

1.3.3 DER Technology Integration

When DERs connect to an electric power grid in the United States, IEEE Std. 1547 applies to most of those interconnections. This leads electric utilities and regulators to ask similar questions of and impose similar requirements on all individual DER connections, regardless of the technology. These requirements apply at the point of common coupling, which is often at the meter. The “prime mover” technology behind the meter is also of concern, but mainly for its effects on variability and uncertainty of supply.

Rather than simply a series of independent DER technology evaluations, EERE research projects need to analyze the combined effects and value of integrated DER technology portfolios. The experience and lessons learned from one type of DER interconnection should also apply to other types of DER interconnections. For example, PV, wind, and water-power DER interconnection processes share many common elements, and the EERE technology offices should not have to relearn each lesson from earlier work. The specific studies required include the following:

1. Integrated energy planning that holistically considers multiple DER technologies, not just one.

2. The aggregated effect of multiple DERs on load shape, not just the summation of individual DERs. Diversity in sizes, locations, and prime energy sources can reduce the effects of variability and uncertainty on the grid.

3. Interaction between rate design and operation of multiple DERs. Economic incentives may induce DER behaviors that mitigate their adverse effects on the grid.

4. Value of integrated DERs to provide grid services and ameliorate negative effects of individual technologies, including bulk-power-sector issues like variable renewable energy curtailment.

5. Different and broader ways to value DERs and fundamental grid components.

6. Calibrated and validated distribution circuit models that are representative of existing systems for credibility, and reusable across EERE for consistency and transparency.

1.3.4 Grid Modernization Laboratory Consortium

The GMLC was established in 2014 to foster the development of a modern electric power grid through collaborations across DOE [22]. Statutory authority comes from the Energy Policy Act of 2005 [23], the Energy Independence and Security Act of 2007 [24], and other legislation.

GMLC priorities have been evolving. The first two rounds of GMLC projects were funded by OE (then called Office of Electricity Delivery and Energy Reliability) and EERE. The first GMLC laboratory call awarded $220M in 2016 to 14 national laboratories, organized into 88 projects in seven areas:

1. foundational, i.e., metrics, valuation, architecture, interoperability, regional partnerships, testing, and several crosscutting topics

2. devices and integrated systems

3. sensing and measurement

4. design and planning tools

5. system operations, power flow, and control

6. security and resilience

7. institutional support.

A second GMLC laboratory call awarded $32M in 2017 to ten national laboratories, organized into seven projects on resilient distribution systems. This call emphasized field validation and regional partnerships with industry and academia.

The third GMLC laboratory call awarded $80M in 2019 to 13 national laboratories, organized into 23 projects. This call specified that “Any proposals including DER must show impact on the bulk power system”. The funding offices broadened to include the Office of Nuclear Energy, Office of Fossil Energy, and the newly formed CESER. The awards were in six topical areas:

1. resilience modeling

2. energy storage and system flexibility

3. advanced sensors and data analytics

4. institutional support and analysis

5. cyber-physical security
6. generation.

To summarize, GMLC has established the relationships and track record for DOE offices and national laboratories to collaborate on larger projects. Some of these projects may have been undertaken even without GMLC, but the larger funding and broader team participation in GMLC has probably increased their effect. This roadmap builds on earlier and ongoing GMLC projects, and not just the ones co-funded by EERE.

In the 2019 GMLC call, emphasis clearly shifted away from distribution systems and DERs. Furthermore, the timing and priorities of any future GMLC laboratory calls are not known. If the priorities align with this roadmap, some of the recommended projects might become GMLC projects. The best course of action for EERE might be to plan this roadmap in collaboration with OE, and then present a joint plan to GMLC leadership. EERE should also consider designating a sustained, unified, planning activity for distribution system and DER research, possibly in the SA Team.

2.0 Research Questions

This section addresses the open questions on DER and distribution system integration from a researcher's perspective. To this end, a list of research questions is developed, categorized, and prioritized, covering technical, operational, and valuation areas. The priority list in Section 2.11 is organized according to functional categories and serves as the precursor to Section 3.0.

2.1 Introduction

DER integration and analysis in distribution systems is a broad area of research that covers multiple technologies (DER generation, storage, and demand-side resources) and analysis domains ranging from the transient response of DERs to distribution network faults, interconnection standards, rate structures, and policy domains. The research questions also span multiple spatial and temporal scales. Their time scales range from microsecond electromagnetic transient (EMT) phenomena to the adoption of DERs across years and decades. Spatially, examinations range from the thermal and electrical characteristics of device elements to those of entire distribution service territories and their interaction with the bulk power system. These domains, namely, temporal, analysis, spatial, devices/DERs, and infrastructures are represented in Figure 6.

Analysis domains can typically be tied to temporal ranges. In the microsecond-to-second range, the transient phenomena of the network and DER operation and controls are important: examining response to faults, system protection, DER controls, and potential frequency control from these devices. In the second-to-minute range, time-series analysis of DERs, the network, and sources or sinks of active and reactive power become important, to understand the steady-state network loading and system voltages. From months to years, analysis starts to include markets and economics, asset planning, and policy development for DER integration.

The penetration of large amounts of DER requires characterizing power systems at increasing spatial scales, ranging from a high-resolution, device level to responses across multiple service territories at different voltage and power levels as DER displaces traditional bulk system generation. The extant literature and many of the reported DER interconnection studies have examined effects of integration on power system domains in individual distribution service territories without scaling to transmission and distribution interaction at a state or national level. The interconnected nature of the power infrastructure across spatial scales raises some key research challenges: scalability and simulations at scale, managing multiple jurisdictions, interconnection standards, and characteristics of different service territories, and resolution of models from the grid edge to the bulk system.

The distribution network interacts with other major infrastructures and domains, such as transportation, communication, water, and gas networks, plus human decision-making behaviors. Analysis of the coupling of these domains is becoming more important as more direct integration between these infrastructures is established through DER and other emerging technologies. For example, the electrification of transport is shifting a major energy vector to the distribution network, and the planning and operation of EV charging must be accounted for in network planning and operation. Similar integration developments are happening in other infrastructures and domains, such as increased communications on the distribution network for sensing, measurement, and control. Having the ability to co-simulate or conduct more-detailed distribution analysis with these domains and infrastructures is an ongoing challenge for DER and distribution system analysis.

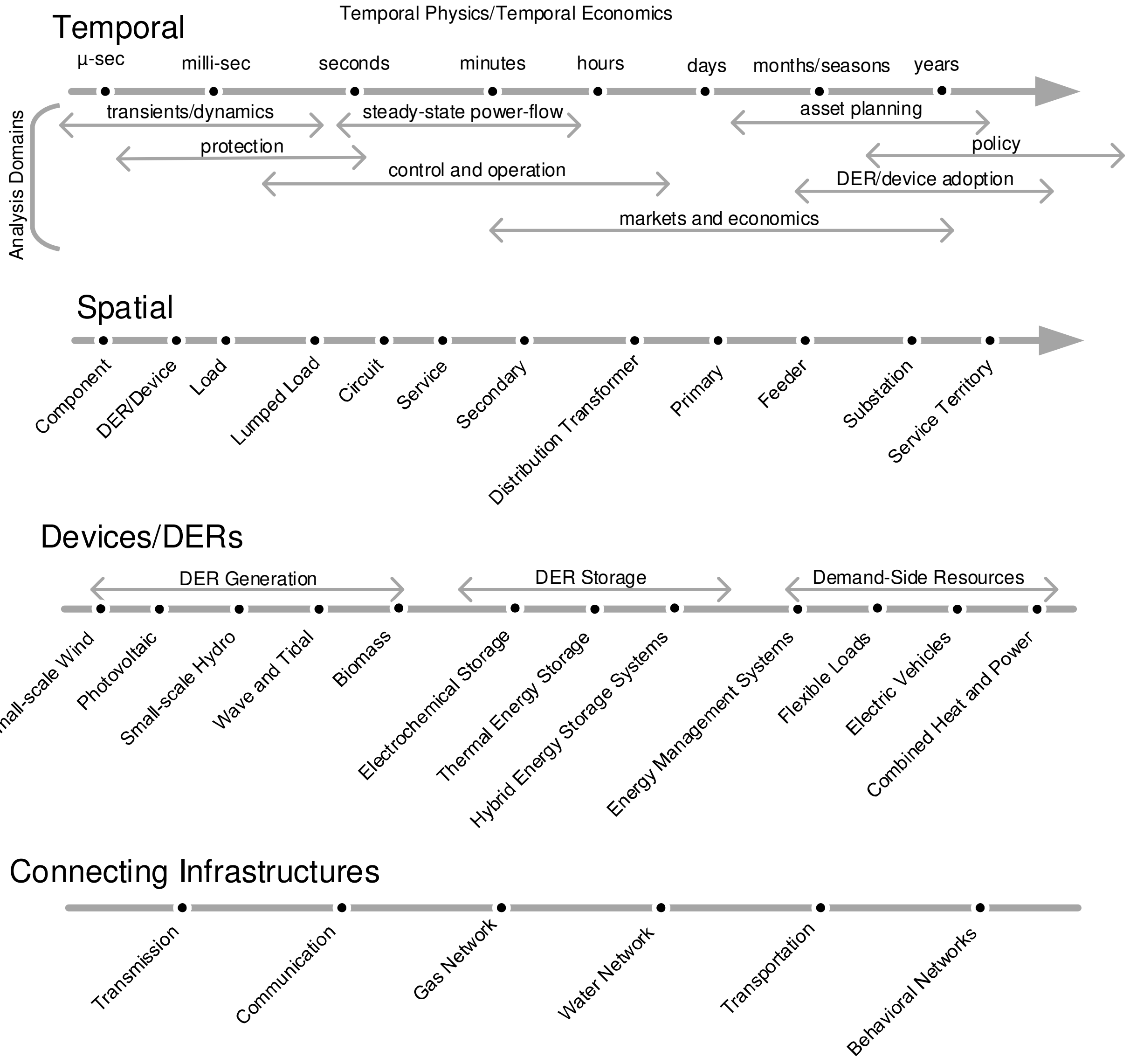

Figure 6. Research domains for DER span time, space, device types and connecting infrastructures.

2.2 Stability

In the context of the bulk system, inertia refers to the ability of the system to resist changes in frequency because the rotating synchronous generators are electromagnetically coupled with the grid. In response to a generation loss, the kinetic energy of these rotating masses is converted into electrical power, thus arresting the decrease in grid frequency. This inertial response provides crucial seconds for primary and secondary frequency responses to intervene and take corrective actions. Hence, large inertia, or the equivalent response, is a desirable characteristic of an interconnection.

Inverter-based DERs such as solar PV, wind, and energy storage do not provide inertial response naturally. The decreased capability of the system to provide inertial response raises concern as they continue to displace conventional generation. Inverter-based DER resources can be programmed to provide frequency response. Currently, the inverter-based technology is dominated by grid-following inverters and controllers that have been designed to respond to changes in frequency by changing the current injection to the grid. However, the grid-following inverters require an external reference from the online synchronous generators to determine their output. Hence, their operation may be limited in low-inertia or weak interconnections.

2.2.1 Grid-Forming Inverters and Microgrids

Grid-forming inverters can synthesize voltage and frequency waveforms without any reference from synchronous generators. Such inverters have been deployed in low- or zero-inertia systems such as islanded microgrids. They can be combined with grid-following inverters, where a grid-forming inverter provides the reference waveforms for grid-following inverters in the system. Though this technology is hailed as a significant step toward achieving higher DER penetrations, some research questions have arisen:

- Frequency response from inverters is highly dependent on the quality of grid frequency measurement. What methods can measure frequency reliably, reject measurement noise, and produce fast measurement times? These are critical to achieving a frequency response that is comparable to the inertial response from conventional generators.

- What new interconnection standards and specifications are needed? Current standards such as IEEE 1547-2018 mention, but do not standardize, grid-forming inverters and islanded microgrids.

- How should control actions be partitioned across various time scales?

- How much communication is required between grid-forming inverters to ensure grid stability?

- Can grid-forming inverters provide primary/secondary/tertiary frequency response without communication?

- When should intentional islanding (microgrids) be used? How should islands be designed, controlled, and coordinated, both at the device level (DER) and at the system level?

- What standards are needed to make sure that DERs are microgrid capable? How should transitions from islanded to grid-connected be done to maximize power quality? What inverter capabilities are required for a black start, and how should the coordination of multiple DERs be managed for black-start capabilities?

- How can DERs and microgrids help improve the real-time resilience of distribution systems? What mathematical frameworks and quantifying metrics are required to rigorously assess real-time resilience?

2.2.2 Grid Support Functions from DERs

DER devices have been proven capable of providing network support to enhance system stability, and some mandates that they do so have been established (Rule 21, Rule 14H, IEEE 1547). Inverter-based devices have been proven to provide steady-state local voltage control (e.g., volt-var and volt-watt), dynamic voltage response (e.g., voltage ride-through), and dynamic frequency response (e.g., frequency-watt). DERs can be used solely to mitigate their own network effects (e.g., PV interconnections using reactive power control to reduce voltage rise caused by injection of active power). DERs can also provide grid support beyond mitigation of local effects (e.g., frequency-watt control). Key questions on DER grid support are:

- How can DERs can use local control to mitigate negative network effects of the DER (e.g., voltage rise induced by distributed generation) and help avoid network upgrade costs?
- How can DER provide separate control functions that complement grid objectives? For example, volt-var control may contribute to CVR in addition to mitigating DER effects.
- The foundation for all microgrids is the ability of DERs to form a microgrid, because they are both leaders and followers of frequency and voltage control and coordination. How can single and multiple DERs detect the correct grid conditions to be grid-forming or grid-following as appropriate?

2.2.3 Fault Current Contribution from Inverter-Based DERs

Fault currents from inverter-based DERs are not as high as those from traditional synchronous generators. However, the nature of these currents is different and is usually specific to the mode of operation and the manufacturer. During faults, the transient current peak can be large (2–3 p.u), but has a very short duration (around 0.1 ms). Although the transient fault current is very short lived, it is strong enough to cause damage. Traditional protection schemes do not intervene on such a time scale. The transient current is followed by a steady-state fault current of 1.1–1.2 p.u. (can be higher for grid forming inverters) that lasts until the inverter enters the momentary cessation phase [25]. Key questions on this topic include:

- What new protection schemes are needed for DER transient currents?
- How should protective devices be coordinated through the time-current envelope of DER fault current contributions?

2.3 Variability

This subsection describes the effects of DER variability, which is an irreducible and undispatchable change in output with time. The related effects, of DER uncertainty, are discussed in a later subsection. Unlike conventional generation, the power output of DERs like solar PV and wind is intermittent and intrinsically variable. This supply-side variability requires more generation flexibility to balance the system. In particular, key challenges related to DER variability include the following three effects:

- More operating reserves: The system operators are required to maintain sufficient operating reserves from conventional generators to balance the system. This translates directly into higher operating costs.
- More switching of voltage regulation equipment: The variable power (and current) output of DERs will cause the voltage to vary across the distribution feeder's impedance, which requires the voltage regulation equipment to switch frequently. This reduces the life expectancy of load tap changers, voltage regulators, and switched capacitor banks.
- Decreased efficiency and life of fossil-fueled generators: To accommodate the variations in DER output, conventional generators may turn on and off more frequently or may change their output more often than recommended. This reduces efficiency and increases wear and tear of the coal- or natural gas-fired plants. Other adverse effects include higher maintenance costs and the associated downtime [26].

The key research questions concerning variability can be summarized as follows:

- How can the penetration of renewable-based DER be increased without using significant reserves from conventional generators?
- How does DER variability affect power quality and coordinated operation of distribution system devices such as voltage regulators and protection equipment?
- How can DER help the balancing authority area optimize dispatch to reduce regulating reserve?
- How should energy storage be deployed to suppress DER variation?
- What new designs for flexible markets and demand-side energy management will be needed?

2.3.1 Advanced Control and Coordination of DERs

Generation and load flexibility can be increased by coordinating and controlling DER dispatch. A variety of control architectures for DERs are being proposed, representing different states of the art and use cases, that include cost and reliability considerations regarding communication, efficacy, and resilience. These control architectures include the following variations:

- Centralized: Centralized architecture has one source/one controller that monitors, controls, and dispatches network assets and DERs. This is typically formulated as a single optimization problem for coordination of devices to meet an overarching objective.
- Distributed: In distributed control, information is shared among controllers to raise overall performance. Control decisions are made at each DER with a combination of local objectives that are informed by shared information.
- Decentralized/Uncoordinated: In decentralized control, decisions are not coordinated among devices and are purely based on local sensing and measurement. The control parameters here are usually fit-and-forget and communications free. They typically are very reliable as a result, but with the sacrifice of suboptimal control decisions.

- Hierarchical: Hierarchical control involves a hybrid mixture of centralized and decentralized control, with a hierarchy of primary (field level/device level), secondary (microgrid level), and tertiary (grid level) control levels.

The control architectures all have trade-offs between optimality of outcome, flexibility of control, communication burden, cybersecurity concerns, and overall cost of implementation. The objective of the control schemes also needs to be evaluated, based on cost, barriers to implementation, benefit of outcomes, reliability, and the cost of any alternatives.

Advanced solutions for management and control of DERs from the utility domain include distributed energy resource management systems (DERMS) and ADMS, which are centralized control architectures. The traditional distribution management system paradigm is also changing with these advanced emerging technologies and the keen interest in operating autonomous microgrids. Beyond the development of microgrids, similar control systems are required at building and residential sizes. Consequently, there is now a growing interest in multiscale optimization and control systems with the widespread adoption of DERs on electricity grids.

DERs can be used to provide capacity-based grid services, e.g., for energy arbitrage, reserve capacity, to alleviate network congestion constraints, provide local balancing, etc., or for ancillary services. This can be achieved through microgrid control, aggregation, or virtual power plants. Fit-for-purpose designs of market structures, communication networks, and control algorithms are needed to achieve this.

The key research questions are:

- What design processes should be followed for the centralized, distributed, and hierarchical control options?
- How can different control architectures be deployed to ADMS, DERMS, aggregators, or other frameworks?

2.3.2 Ancillary Service Provision

Providing ancillary service from DERs can be done at either the distribution or bulk system level. Distribution-level ancillary services are much more readily achievable, while bulk systems involve challenges in consolidating local network constraints with bulk system needs. Transferring active and reactive power from the distribution network to the bulk system for capacity provision is also an issue. Distribution ancillary services can be for both alleviating DER network effects and providing grid support services.

The key research questions around DER ancillary service provision include the following:

- How can DERs be deployed to simultaneously provide distribution and bulk system services considering the possibility of competing objectives at times?
- How should ancillary services from DER be quantified at the bulk level?
- How do the performance, cost, and reliability of ancillary services from bulk generation compare with those from DERs?
- Can these services be simultaneously provided while maintaining a financially viable project for the system owner? What market or compensation approaches (if not current ones) could enable that?
- What proven methods are available for aggregating multiscale DERs to provide ancillary services?

2.3.3 DER Dispatch and Optimization

Successful dispatch of DER depends on the flexibility of the resource, its capacity to provide that service, the availability and visibility of system information, the speed and resilience of communication, and interoperability among other elements. The challenges in DER control and optimization can be broadly categorized as the solution methods, information and communication, and DER capabilities:

- Solution methods: Different approaches to solving must be able to deal with multiple challenges, such as scalability and tractability of the problem formulation (particularly when dealing with aggregate DER control), computational capability requirements, translating multiple objectives (such as economics, reliability, and resilience), and dealing with sources of uncertainty (e.g., weather, availability of DER functions, etc.)

- Information and communication: The availability of information for control decisions relies on sensing and measurement and communications infrastructure. The required availability of information depends on the overall control architecture (centralized, distributed, decentralized, or hybrid). There are multiple challenges and opportunities as to the availability of information, such as the development of hybrid communication networks (e.g., combining supervisory control and data acquisition [SCADA] and advanced metering infrastructure [AMI] networks), cybersecurity concerns, and the need for device interoperability. The frequency and resilience of control signals and the ability to forecast and extrapolate or develop proxies to fill information gaps are also required.

- DER capabilities: To provide the required control, DER dispatch systems must be able to characterize DER and the flexibility and resilience of the resource, assess response times, and characterize the availability of the resource while online.

The key research questions are:

- Can the existing optimization tools scale up to systems with millions of DER? If not, what new developments are needed?

- What data and communications capabilities are needed to optimally dispatch systems with millions of DER?

2.4 Security

As smart grid technologies, including DERs and advanced sensing and communication technologies, proliferate and become indispensable on distribution systems, cybersecurity must be upgraded accordingly for safe and reliable distribution system operation. The increasing penetration of DERs calls for planning to maintain power system reliability, resilience, and security. Cybersecure operation of the distribution system will require advances in communications and security, development of standards, and finding low-cost means to implementation.

2.4.1 Cybersecurity

Utilities are increasingly exposed to cyber threats with the growth of communication networks and communication-enabled devices, including DER and flexible loads. DERMS functions enable the aggregation of DERs to provide bulk services and interact with distribution network assets (e.g., load tap changers, capacitor banks, etc.). Compromised aggregation of DER devices, for malicious intent or through some control failure, may cause large-scale coordination of operation that may result in widespread outages (e.g., the cybersecurity threat from malicious coordinated operation of smart thermostats). As buildings adopt communications-enabled DERs, the cyber threat landscape is rapidly evolving.

The key distribution system cybersecurity research questions are:

- How can utilities best transition to reliable, cybersecure distribution system operation business models?
- What are the risks of coordinating operation of DERs and cloud-connected home loads?
- How can we protect personal data on AMI networks?
- How can we secure ADMS and DERMS communication networks?

2.4.2 Protection

One major effect of DER integration into distribution system operation is the challenges to system protection [27]. Specifically, DER generation is a non-utility source that can inject more current into network faults. This introduces challenges to network protection, to detect and isolate faults on the network. The fast response of inverter-based DER controllers means their contributions to system fault current tend to vary; currently, their fault response is very manufacturer dependent. Advanced distribution protection schemes might be adapted for high penetration of DERs on the distribution system. These key protection questions should be addressed:

- How do inverters respond to grid faults? What methods can be used to estimate DER contribution to different types of distribution system faults?
- Are current standards adequate for protection system modeling and design?
- What methods can be used to implement centralized and decentralized fault location, isolation, and service restoration (FLISR) applications of DERMS and DERs?
- How should distribution system protection schemes evolve from unidirectional flow of fault current? The distributed nature of various DER interconnection scenarios within the distribution system may necessitate the design of new protection coordination schemes. Candidate schemes for distribution systems with DERs include multi-agent, adaptive relaying, and online-adaptive overcurrent protection techniques. Which are most appropriate?
- How might protection schemes evolve to configure their responses to extreme events (e.g., extreme weather)? How might protection schemes evolve to enable resilience and more stringent reliability criteria (e.g., $N-2$ contingencies or greater)?
- How should optimal network reconfiguration methods be designed to promote self-healing in distribution networks under fault conditions?
- How should protection schemes for islanded microgrids be designed, controlled, and coordinated?

2.4.3 Physical Security

Conventional generation facilities and utility-scale DERs are secured by fences, perimeter security, and controlled access areas, but BTM DERs installed at customers' premises are easily accessible and thus prone to physical damage. These devices can be physically tampered with to generate a network fault, which poses a serious risk to network operation and customers' premises. Moreover, physical access to the DER interface can be used to steal or manipulate metering data and to gain unauthorized access to the communications infrastructure. Three questions about ways to reduce the risk of physical damage are:

- Can tampering detection mechanisms shut down DER operation in the event of a breach? Should they just raise alarms for the customer and the utility?
- How can DER deployment practices minimize access to unauthorized people?
- How can we minimize exposed interfaces on DER devices, and secure them with encryption or other data-securing methods?

2.5 Uncertainty

The presence and adoption of DERs introduces a new source of uncertainty that poses new challenges to the operation, planning, and regulation of distribution networks. The uncertainty introduced by DERs can be either

- short term—related to power production of from existing renewable-based DERs, or
- long term—related to private DER adoption decisions and the long-term penetration of DER capacity behind the meter.

On an operational scale, the uncertainty of renewable DER generation may cause unpredictable imbalances in the power system; these affect reliability standards, aggravate reserve requirements, and increase the overall system operational costs. Despite improvements in forecasting technologies, this uncertainty represents a risk to system operation, which is managed by applying conservative strategies, such as active curtailment or market limitations on intermittent resources, that represent a barrier to the adoption of DER technologies (particularly PV and wind). These strategies rely on defensive treatments of uncertainty, based on improbable combinations of worst-case scenarios, and fail to capture the actual risk of the system.

Furthermore, the difficulty of managing DER uncertainty increases with the time horizon, as we move from operational decisions (hours ahead) to an investment and planning scale (years ahead). In the planning phase, long-term uncertainties (such as those related to the magnitude and location of candidate PV) can pose severe challenges to the utilities and system operators when considering new grid assets. Improper management of the uncertainty results either in overinvestment in PV and high system costs or in underinvestment and limited PV hosting capacity. Therefore, controlling the risk in the planning phase and addressing the long-term uncertainties of variable DERs is key to decreasing integration costs and unlocking grid hosting capacity.

Thus, the key research questions in this area focus on reducing uncertainty and on including it in the decision-making process:

- How can we develop improved forecasting methods to predict renewable-based DER generation at the distribution level to reduce the short-term operational uncertainty? This can include improvements in data quality and measurements.
- How can we improve current adoption and diffusion models to mitigate the uncertainty associated with long-term deployment of BTM DER technologies?
- How can we integrate short-term and long-term uncertainties in distribution network planning and operation decisions, particularly in scenarios of massive penetration of DERs?
- How can we quantify and mitigate the security and economic risks associated with the uncertainty of DERs?
- How can we use dispatchable resources (e.g., storage or demand response) as risk-hedging assets to control distribution system uncertainty?

2.6 Situational Awareness

The power system continues to transition from a centralized network to a highly decentralized system as a result of increasing DER penetrations, independent generators, and prosumers (A prosumer can generate as well as consume energy). Capability to observe this complicated network of independent and interdependent actors is critical to stable grid operation. Different domains of the power system use multiple layers of sensors, actuators, and transducers to monitor and control power quality, voltage level, and power flow through power delivery elements for safe and reliable operation of the grid. One key challenge is the siloed deployment of novel and advanced sensors across greater distances ranging from centralized power generation to end-use systems. One reason for the transition may be the combination of enormous communication technologies and network requirements with data analytics requirements to enable integrated deployment of these devices across grid domains.

2.6.1 Sensors and Analytics

Sensing and measurement for distribution systems have become pivotal with the changing topological structures and system dynamics caused by the increasing penetration of DERs and other grid-edge devices that must report data. Also, the limited visibility within the distribution system and the multitude of needs at the grid edge creates the need to develop low-cost sensing and measurement strategies.

As the distribution network continues its topologically complex evolution, system operators need grid state information to make grid control decisions. Consequently, utilities need to develop a strategy for robust observability and system state sensing to provide a framework for implementing grid sensing and measurement across various temporal and spatial dimensions. This presents another constraint: how to instrument extended grid states (such as ambient, topological, building, and electrical states) for the complex distribution system topologies with the growing extent of DERs and other grid-edge devices. This implementation must also be achieved in a cost-effective way that maintains secure grid operations. Some of the key areas to investigate include the following:

- What new low-cost sensing methods would enable optimal placement and wider deployment of new sensors, while maintaining performance comparable to that of the existing sensing devices [28]?

- Would wireless, self-powered, and self-calibrating sensors reduce total cost?
- Do we need new material processing and manufacturing facilities to create sensors that are not producible by conventional methods?
- How can sensor lifetimes be increased, especially to survive in extreme climates and extreme events?
- How can we develop highly interoperable sensors that work with existing and future communication infrastructure?
- How can we overcome the impediments to data integration, standardize data formats, and simplify analytical tools?

2.6.2 Communications and Interoperability

The heterogeneous characteristics that exist among legacy and evolving communication technologies within the distribution system make interoperability a major issue, particularly in the absence of universally adopted standards. As DERs and new communication networks are deployed on the distribution network, reassessments are needed from the perspective of evolving security, reliability, and communications and control requirements. To achieve interoperability, that assessment should be used to develop and converge common communication protocols for standards development and policy adoption. For standards development, the requirements must be assessed from cybersecurity and controls perspectives to enable secure communication and interoperability of DERs with associated power system interfaces. The following are some of the major communications challenges and opportunities facing distribution networks:

- How should information from AMI be secured? How should AMI data be used for increasing monitoring and control?
- What new DER cybersecurity, controls, and interoperability requirements are needed for standards development and policy adoption?
- Are new communication protocols needed for DER in ADMS and DERMS?
- How can we enable hybrid communication networks from AMI, SCADA, and other sensing and measurement equipment (e.g., DERs)?
- What methods enable co-optimization of distribution and communications (e.g., internet fiber-optic network)?
- Increased interoperability may render a DER less cyber secure. What is the proper balance between interoperability and cybersecurity?
- What gaps exist in IEEE Std 2030 for DER interoperability and cybersecurity?
- What gaps exist in IEEE Std 1815, (i.e., DNP3), for DER interoperability and cybersecurity?
- Does IEC 61850 offer significant advantages over the family of IEEE standards for DER interoperability and cybersecurity?

The key research question is how utilities and other stakeholders can determine the optimal mix of legacy and evolving communication technologies to ensure cybersecure operation of the distribution system.

2.7 Electrification of the Economy

Electrification of important sectors of the economy and society (government, health, information, industry, etc.) has made power distribution vital for communities' life and safety. The distribution network interacts with other major infrastructures and domains undergoing electrification, such as transportation, buildings, and industry. Hence, analysis of the coupling of these domains is becoming more important. For example, the electrification of transport moves a major energy vector to the distribution network, and network planning and operation must account for EV charging needs. Having the ability to co-simulate or conduct more-detailed distribution analysis with these domains and infrastructures is an ongoing challenge for distribution system analysis.

The urban energyshed concept (distant effects of power supplied to a city), as recently published in a high-impact journal [29], is one example of how regional planners might consider transforming the electric power system for compelling economic or environmental reasons. The authors use DC power flow and other simplifying assumptions that an experienced power system engineer would question. However, questions of technical detail could not impeach the motives for electric grid transformation. A more productive response would be to provide usable, ”good enough” models of DERs and the grid to support valid, holistic analysis of grid transformation. The tools and models developed in this roadmap should yield the broadest possible applicability in studies of the national economy.

The key research topics on electrification and co-simulation of infrastructures are:

- How can the planning and design of both the distribution network and EV charging infrastructure be co-optimized [30]? How should network constraints on both systems be valued against each other? How much volume will fast DC chargers require for level 1 (120 V AC) versus level 2 (240 V AC) charging?

- How can charging patterns that are related to both consumer behavior and the physics of EV operation and discharge be successfully modeled? How can charging patterns be motivated to minimize the cost of charging through optimized scheduling to reduce both energy and fixed capacity (i.e., network infrastructure) costs?

- How can EV charging minimize grid impacts and what is the potential for V2G operation? What value must be provided to the consumer for EVs to participate in any grid services, and how reliable is that service provision?

- How should water and distribution network interactions that constitute electricity demand and production be modeled? These include (a) small-hydro and run-of-river applications used for power generation in remote areas, (b) water end uses such as purification and hot water heating that serve as flexible loads, (c) demand response resources such as electric hot water heaters, solar thermal facilities used for water heating, agriculture, and water pumping efficiencies for rural networks. Moreover, water conservation—particularly methods that reduce hot water consumption—and efficiency can also provide grid benefits, reducing the need for electric heating.

- Electricity supply is vital for energy-intensive water treatment processes such as purification and desalination. Similarly, wastewater handling plants and water supply infrastructure also depend on a reliable supply of electricity. Historically, extreme weather events have severely disrupted the water supply for days or even weeks. Can we use DERs to reinforce the resilience of water supply infrastructure and associated water treatment and handling processes?

- In the natural gas infrastructure, small-scale distributed natural gas-fueled generation and CHP are resources integrated into the electric power distribution network. Gas-fed energy consumption on the demand side currently alleviates consumption that could have been sourced from electricity. There is an increasing focus on electrifying these demand-side technologies, which will greatly increase load on the distribution network. How should interactions between the electric power distribution network and gas infrastructure be captured?
- What are the effects of infrastructure electrification on load shapes? Can we influence these load shapes and reduce operating costs?
- What are the effects of new consumer choice models for end-use technologies on the distribution system?
- What advanced behavioral models are needed to capture nuances of consumer EV driving and charging, which affects the distribution system?
- Effects of individual DER technologies have been studied (e.g., solar integration). What new studies are needed that examine the interactive effects of multiple DER technologies (e.g., generation, storage, and demand-side resources)? How might diverse DERs mitigate or exacerbate the effects of any single technology?

2.8 Energy Equity

Electrification should go hand-in-hand with energy equity: everyone should have fair access to clean, affordable energy without discrimination based on factors such as income, race, or gender [31, 32]. Some of the major research topics in this area are listed here:

- Low-income households typically have a high energy cost burden, older appliances, and building material with low energy efficiency. What new energy efficiency and renewable energy programs for low-income households should be developed?
- How should the energy consumption characteristics of low-income households and underserved communities inform program planning and the decision-making process?
- Are there more optimal ways to deploy and economically share DERs, such as community solar, in communities such as low-income neighborhoods?
- Communities that are underserved and traditionally subjected to discrimination often live near polluting facilities such as fossil fuel-based plants. What are the possible health benefits of DER to these communities from better local access to clean energy?
- How should economic incentives for DER be split between property owners and renters, considering that many people with low income levels live in multifamily dwellings?
- What new metrics would quantify energy equity? These metrics are essential for measuring the current state of equity and the incremental improvement achieved through energy equity programs.

2.9 Valuing DERs

Flexibility is the ability of the grid to balance demand with supply as they change [33]. Although all power systems are flexible, increasing levels of variable generation resources (e.g., many DERs), will require modern power systems to have more flexibility. Common methods to achieve higher flexibility include designing DSM approaches, creating advanced markets and coordinating their operation, and improving ramping capabilities of conventional generators.

2.9.1 Utility Retail Rate Structures and Demand-Side Solutions

Utility retail rate structures have been evolving to accommodate demand-side changes in terms of both demand response and BTM resources such as DER generation and storage. TOU rate plans have encouraged both reducing energy use and shifting consumption from on-peak to off-peak hours. Coupling TOU rates with information programs has made customers more aware of energy consumption patterns and ways to increase energy efficiency. Rate structures that motivate demand response and increased efficiency have included TOU, CPP, peak-time rebates, and demand charges.

Another challenge facing utilities has two aspects: fairly motivating BTM generation, particularly solar PV, while ensuring that fixed costs are adequately recovered. Utility kilowatt-hour prices include both energy and capacity components (i.e., network and generation capacity), and while solar offsets customer energy requirements, it does not necessarily offset utility capacity costs. Furthermore, in some extreme scenarios, high DER penetration can increase fixed-cost elements by requiring network upgrades to increase network hosting capacities. This means that utilities need to change their kilowatt-hour price structures to a form that ensures they can recover their fixed costs. At low solar penetration rates, some utilities have opted to use net-energy-metering rate structures, because recovering fixed costs is not an appreciable challenge at low solar penetration rates. But with increased penetration, utilities have moved to a variety of retail rate structures that include feed-in tariffs, demand charges, and zero-export policies. These retail rates prohibit or place little value on the export of generation to the grid. Implementation of these rates encourages customers to use as much of the generation locally as they can; this motivates BTM storage and demand-side solutions to match load with local generation (e.g., HEMS).

As rate structures motivate adoption of BTM storage to best use BTM generation, the rate structure must adequately motivate charging and discharging to yield an overall benefit to the load profile (i.e., reducing peaks, leveling loads, and reducing net load ramps). The key research questions are:

- What new retail rate structures could motivate adoption of BTM storage?
- How does this adoption complicate utilities’ optimization of the overall load profile?

2.9.2 Advanced Market Structures

As DER generation and storage penetration increase on the distribution network, traditional unidirectional retail rate structures (customers settling monthly with utilities) may be drastically changed. Changes could allow customers to be both price makers and price takers, bidding for local generation and then also selling power locally among communities to other market participants. These advanced markets would require a complete overhaul of current utility pricing mechanisms and require advanced communications.

Transactive energy markets, possibly incorporating blockchain for security and transparency [34], could enable millions of BTM resources to trade energy as a form of peer-to-peer trading. There is a large volume of research on achieving such a market [35, 36, 37, 38]. Topics include ways to establish prices for customer end uses, prices for generation and storage, the value of reliability and sustainability, and the willingness of customers to enter such a market arrangement. However, such markets can also expose customers to the volatility of the wholesale market. Thus, it is imperative to devise methods that shield the transactive markets and the customers from price spikes in the wholesale market. Other challenges to implementation include communications, privacy, real-time transaction, and incorporation of distribution losses and fixed-cost components (i.e., generation and network assets).

Other advanced market structures involve moving to distributed nodal pricing and real-time markets for customers. The key research questions are summarized here:

- What are the potential benefits of using transactive energy markets? What are the associated distribution network challenges?
- How should optimal real-time prices be established for customer end uses and for generation and storage?
- How can reliability and sustainability be ensured for such markets? What mechanisms are needed to encourage customer participation?
- How should transactive markets and customers be shielded from the volatility in the wholesale market, such as price spikes?
- How should reliable communication, privacy, and real-time transaction be ensured?

2.10 Network Design for Accommodating DER

Designing distribution networks to accommodate increasing DER penetrations with high reliability poses an interesting set of research questions. Usually, network design involves replacing older assets that are at end of life, reinforcing weaker sections, and planning for load growth or DER adoption. A complete network design at the fundamental level is usually not considered. The current design has effectively supplied power to communities across the U.S. for decades. Designing/redesigning the overall network is logistically and economically challenging.

Multiple research topics explore network design to accommodate DERs and increase overall reliability and resilience. They include the following:

- Meshed vs. radial networks: Distribution networks have a principally radial topology, branching out from the distribution substations from medium-voltage primary circuits to (sometimes networked) secondaries and service lines. The radial primary structure was originally adopted because it was less expensive to deploy. Meshed configurations are used in some highly urban (e.g., downtown) networks as a way to provide increased reliability. Meshed networks, or radial networks with normally open tie points, allow for network reconfiguration that can increase capacity, reliability, and resilience. Meshed networks can provide $N-2$ levels of reliability, with multiple paths to provide power to customers. While meshed networks provide increased reliability to customers, they also pose a challenge to fault isolation and protection in the presence of DER generation. As a result, many utilities do not permit any generation export (or meter backfeed) by customers connected to meshed networks.

- Spacer cable systems: Spacer cables, when used in a radial system, can provide some reliability benefits of meshed systems. They consist of covered phase conductors held together and supported by a high strength messenger cable, and connected to diamond-shaped spacers every 30 feet. The conductors are covered with two or three layers of insulation, which allows intermittent contact with ground and tree branches without causing a fault. These cables are especially useful for areas with trees and right-of-way concerns. In addition to higher reliability, they reduce tree trimming costs, improve aesthetics, and are more flexible. For DER integration, spacer cables provide the benefit of smaller positive-sequence impedance than conventional overhead distribution lines. This reduces the magnitude of voltage fluctuation caused by DER variation. It also increases fault current, but that effect is usually less important.

- Power electronic devices in the network: The use of power electronic devices (PEDs) as both a replacement for traditional regulator equipment on distribution networks (e.g., solid-state transformers) or for new use cases (e.g., back-to-back converters at normally open points) is an emerging avenue of research. The back-to-back (B2B) converter is a good example of a new network design use case, having complete control over power transfer at normally open points. One key characteristic of the B2B converter is the ability to provide fast control of power flow to the grid at a constant DC-link voltage. [39, 40]. However, a key barrier to PED deployment in the distribution system is the ability to analyze the value of the ancillary benefits enabled by such devices (e.g., enhanced voltage control) against their cost and reliability. Designers considering enhancements from PEDs should explore how they can aid DER integration. Solid-state transformers can help increase DER penetration by enabling sophisticated grid-edge voltage and frequency control [41]. PEDs can enhance regulation capabilities, which also can aid DER integration. Another barrier is the relatively high cost of PEDs compared to conventional transformers, load-break switches, and fuses. Thus, to justify PEDs, multiple new value streams must be quantified.

- DC grids: The use of power electronics enables the use of DC grids, whether simply for DER coupling (e.g., DC-coupled solar+battery systems), or DC pico-grids for BTM applications [42]. With more DC devices requiring AC conversion, there may be advantages to using small DC grids, which could reduce the need for multiple conversion circuits at each device's point of coupling.

- Microgrids: Microgrids can be used to locally balance DER generation and demand and to increase reliability and resilience. Microgrids can be used as a form of grid planning, serving as both an energy harvesting network for DER and energy distribution. Balancing within a microgrid can reduce the need for imports from the bulk system. Trading mechanisms can be set up to exchange energy within a microgrid or between networked microgrids. Balancing supply and demand among a network of microgrids may be an alternative to bulk system generation. Integrated bulk and distribution technoeconomic analysis is required to assess the overall economic and reliability benefits of networked microgrids compared to bulk system generation remaining the principal means of energy generation.

- Shared Hosting Capacity: Conventional DER interconnection processes charge the full cost of distribution system upgrades to the last applicant who created the need. Prior and future DER applicants may benefit from these upgrades without paying for them. Furthermore, a high interconnection cost for one project can halt further DER adoption on the circuit. A DER-ready feeder design would share upgraded communications, protection, and control among all DER applicants. The resulting system should be more optimal.

In considering these network design options, the key research questions are:

- How can urban distribution networks, in particular, be designed and operated to accommodate more DER?
- What changes to equipment and design practices on radial distribution networks would accommodate more DER?
- What new applications of power electronics would accommodate more DER?
- Most of these options provide benefits for the grid as well as DER, raising the issue of how to allocate costs among all the stakeholders. What planning, design, regulatory, and market processes would enable these mutually beneficial improvements?

2.11 Functional Summary and Prioritization

This subsection summarizes the foregoing research questions by functional topic area used in the next section: regulatory, planning, design, operational, and crosscutting issues. The organization shifts from technical research topic to industry function, which is better suited to presenting gaps, capabilities and the roadmap to potential sponsors and adopters.

2.11.1 Regulatory Issues

These external factors influence how utilities and DER stakeholders may operate. Figure 7 provides a framework for analysis of how changes in policy and regulation could affect the outcomes for utilities and DER stakeholders.

- How should stakeholders deal with uncertainty in policy and regulation? Future utility decisions will be made under high uncertainty. Utilities and developers show skepticism in deploying more DERs because of the risk and uncertainties presented by factors such as full-service impacts, pollution, regulation, technology advancements, fuel prices (especially natural gas), and changing regulatory frameworks.
- How can grid reliability performance be measured and evaluated in ways that reflect outages experienced by the consumers in scenarios where a significant portion of the energy is generated behind the meter?
- How should economically efficient incentives be designed for deployment of DERs that reflect their ability to increase resilience across electric utility customer classes?
- How can retail tariffs be created that adequately promote peak reduction and energy efficiency, fairly price DER generation exported to the grid, and promote proper use of DER storage?
- How do rate design and DER compensation mechanisms affect the adoption and operation of DERs, and what are the resulting costs and benefits to the distribution system?
- An increasing challenge for electricity retail markets in the presence of DER is energy equity, which can be examined through the levelized cost of electricity. Customers who can afford DERs, energy efficiency measures, HEMS, and the like can lower their levelized electricity

costs, and reduce the percentage cost contribution toward maintaining the network assets and capacity on which they still rely. These costs can then burden customers who cannot afford the cost-saving assets. Retail markets should reasonably disentangle volumetric energy charges from fixed charges so customers are fairly charged based on their need for grid assets. The high up-front capital costs of DERs and energy efficiency measures are a barrier to adoption for economically disadvantaged customers and communities. What alternative market structures (e.g., as-a-service market models) are better routes for deploying DERs for disadvantaged customers?

- How can DERs participate in bulk markets to provide capacity and ancillary services without adversely affecting the distribution network? How should DER participation and service provision be valued in traditional bulk and advanced transactive energy markets?

- When planning for a distribution network is combined with planning for other interacting networks such as transportation, how should the utility planner interact with other planners?

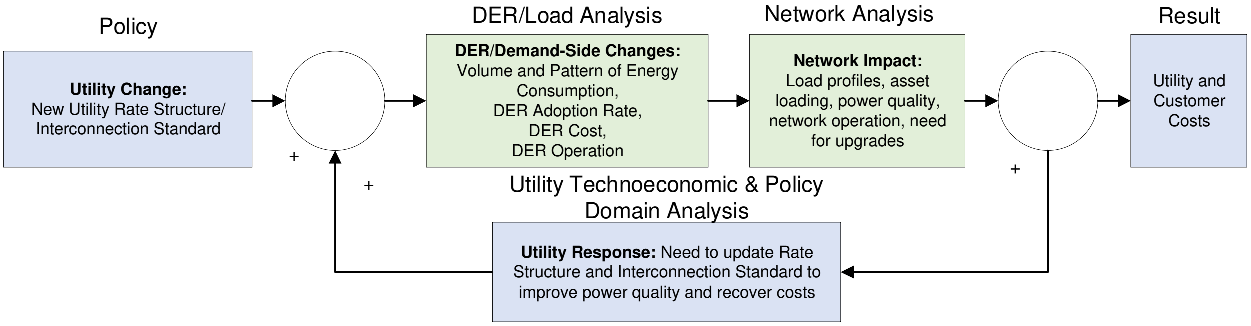

Figure 7. Utility, customer, and DER feedback influences planning and policy.

2.11.2 Planning Issues

Planning, design and operational functions have some overlap. In planning, the DER and grid infrastructure questions are about how much, how many, how large, and the economics. Time frames vary from months to years.

- How can we optimize network infrastructure investments, including substation/circuit upgrades and reinforcements as well as DER sizing and placement? How should we consider the high variability of renewable-based resources and dynamic net-load scenarios caused by the adoption of BTM technologies?

- How should we assess financial and security risk regarding long-term investments on the deployment of DERs and network upgrades, considering stochastic expansion and planning of the distribution system?

- How can DERs and microgrids help improve the real-time resilience of distribution systems?

- Representing diverse DERs is not a standard practice at many utilities. They may employ oversimplified models of DERs with questionable assumptions, and examine the effects of DERs in isolation. Diverse DER modeling practices should be promoted by establishing standard practices and by improving the accessibility and usability of associated model technologies. What is the best way to examine the combined effects of multiple DER technologies (e.g., generation, storage, and demand-side resources)? How do we move beyond separate examination of individual DER technologies (e.g., studies that focus only on solar integration) and consider how diverse DERs may mitigate or exacerbate the effects of any single technology?

2.11.3 Design Issues

Design, planning, and operational functions have some overlap. In design, the focus tends to be on specific equipment ratings, control settings, protection settings, commissioning, etc. There may be some impact on final project cost, but the higher-level cost questions have been answered. Time frames vary from days to months.

- What DER control and coordination methods can be designed to make the distribution network more resilient? To answer this question, first develop DER control and optimization techniques. Second, assess value and reliability of different control architectures, including centralized, distributed, decentralized, and hierarchical. Third, plan controls for the health, safety, and reliability of grid-edge devices, and extending device life.
- What are the design impacts of DER on security? To answer this question, first design mechanisms to deal with uncertainty in information and communication. Second, design cybersecure sensing and multi-networked information platforms (SCADA, AMI, inverter).
- What are the design impacts of DER on protection? To answer this question, first examine PEI fault detection, response, and contribution to system faults. Second, redesign protection for radial and meshed networks.
- How should distribution system protection schemes evolve from unidirectional fault currents? How might protection schemes evolve to accommodate extreme event (e.g., extreme weather) modeling? How might protection schemes enable resilience and more stringent reliability criteria (e.g., $N-2$ contingencies or greater)?
- How should optimal network reconfiguration methods be designed to promote self-healing in distribution networks? How should protection schemes be designed, controlled, and coordinated for islanded microgrids?
- What changes in fundamental network design would facilitate adoption of DERs? Examples may include microgrids, power electronic assets replacing traditional distribution network assets (e.g., back-to-back converters, solid-state transformers), meshed networks, spacer cable systems, and the concept of shared hosting capacity.

2.11.4 Operational Issues

Operational, design, and planning functions have some overlap. In operations, the focus tends to be on using what has already been installed. Dispatch commands and new settings might be possible in real time, if the planning and design processes have provided such capabilities. Utility crews could make some changes in the field, but significant changes to the network or DER would involve re-planning and/or re-design. Time frames, for operations, vary from seconds to days.

- How should the different DER services be valued? Consider mitigation of local DER-induced network effects, provision of grid support services, provision of capacity-based grid support services, bulk vs. distribution system services, providing services without violating local network constraints.

- How do we analyze risks of coordinated operation of DERs and cloud-connected end-use appliances, protection of personal data from end-use loads and AMI data, and cybersecure ADMS and DERMS communications network operation?

- Examine use of hybrid communication networks, AMI, SCADA, and other sensing and measurement technologies. Improve visibility of the grid edge through enhanced monitoring and communication with grid-edge devices. How do these translate into design requirements for the communication networks?

- Consider operational interactions between the distribution network and other infrastructures such as water, transportation, markets, and natural gas. For example, operation of EVs in the transportation network depends on the distribution network. Does a utility need to engage with other companies and regulatory authorities to support this?

- Consider effects of customer choices and behaviors on the rate of electrification of the economy. How do these behaviors affect the load profiles, the day-to-day operations of the utilities, and their response in extreme conditions or events? How does customer behavior affect utilities that rely on demand response?

- How can DER aggregation improve local balancing in microgrid environments on the distribution network? How can it help provide distribution and bulk system services?

2.11.5 Crosscutting Questions of Analytical Capability

The previous sections have described modeling and analysis needs from several perspectives. Research projects may use specific sets of tools and methods, and these sets overlap. For example, volt-var optimization and DER expansion planning both need time-series power flow. However, volt-var optimization needs to represent control action, while DER expansion planning does not. Conversely, DER expansion planning needs to account for years of operation, while volt-var optimization does not. The audience for volt-var optimization might be engineers and operators, while the audience for DER expansion planning might be distribution planners and regulators. The type of audience determines how the tools, e.g., time-series power flow, are used in a research project. The questions for crosscutting analytical capability are:

- What new tools are needed to consistently model and solve DER equations over a wide temporal span ranging from microsecond EMT phenomena to adoption of DERs across years and decades? Spatially, the range should extend from examining the thermal and electrical characteristics of device elements to examining entire distribution service territories and their interaction with the bulk power system.

- What new capabilities and efficiencies are needed in frameworks that model and solve multi-domain systems, especially the Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS)?

- What new algorithms are needed to co-optimize multiple infrastructures? We will need more efficient approaches to solve mixed-integer, nonlinear problems.

- How can forecasting methods be improved to predict DER generation? How can the quality of stochastic models be increased to reduce network modeling uncertainty?
- What is the mathematical foundation for metrics to rigorously assess the resilience of distribution networks?
- What new integrated planning tools can efficiently process a large amount of data to facilitate the study of diverse DER effects?
- What new efficient analytical tools are needed to integrate new equipment such as sensors with minimum effort?
- System-level models of new components developed by the AMO are needed so utilities can integrate them into the electric power distribution system. For example, the designer of a new solid-state transformer might have detailed EMT and finite element models for design purposes, but these are not suited to system integration studies. How does the utility include the new device into basic power-flow and short-circuit studies?

3.0 National Laboratory Capabilities

National laboratories host many programs that can tackle several of the questions discussed previously. This section will summarize the existing distribution-system and DER modeling capabilities within the national laboratory network. It's organized by sponsor and adopter viewpoint, like the preceding functional summary and prioritization of research questions. Once the existing models and tools are mapped to the prioritized research questions and technical challenges from the previous sections, a research roadmap can be formulated.

3.1 Regulatory Functions

DERs can provide several benefits to the distribution system, such as reducing net load at the distribution level, avoiding peak load costs, decreasing the need for ancillary services, deferring investments in the distribution grid, and improving flexibility, among others. However, uncontrolled integration of DERs into the grid can pose challenges to utility planning and operation by increasing hosting capacity costs, introducing equity problems among consumers, and threatening the reliability and resilience of the distribution network. Over the last decade, national laboratories have worked with utilities and public utility commissions (PUCs) to address these issues; they have developed valuation methodologies and helped establish regulatory and policy frameworks to facilitate the integration of DERs into distribution systems while working toward economic, security, and environmental targets.

Lawrence Berkeley National Laboratory (LBNL) projects include development of technical models and tools together with training, reports, and technical assistance to utilities and regulators. Innovative technical tools and models include the Integrated Modeling Tool (IMT) for regulators [43] and the Grid Access Planning model [44], which serve to assess distribution grid security, reliability, and effects of rate design for different DER adoption scenarios. NREL's dGen model simulates different market scenarios that motivate customer adoption at a national, regional, state and local level. Regulators can use dGen to assess future scenarios motivated by policy. Technical assistance products include analyses of regulatory challenges associated with the incorporation of DERs and demand flexibility into distribution system planning, integrated system planning, grid modernization, and forecasting [45]. These reports and the technical assistance, including the Future Electric Utility Regulation series [46], focus on the economic and reliability effects of DERs and how to best capture their value and operate under high adoption levels [47]. In addition to grid planning, LBNL has analyzed how DER adoption may affect utility business models. These reports include ones that focus on how utilities can use price signals such as rates and programs to better align DER operation with grid value. Better alignment could promote beneficial adoption and operation of DERs, which could mitigate adverse grid effects while providing distribution grid services and higher operational efficiency.

LBNL has developed models, analyzed case studies, and performed expert elicitation to better quantify the cost of electric service disruptions and subsequent value in avoiding interruption of service. The Interruption Cost Estimate (ICE) Calculator [48] is designed for utilities, government organizations, or any other entity interested in estimating interruption costs and/or the benefits associated with reliability improvements. NREL tools include the distribution grid integration unit cost database, which provides information on PV integration costs including voltage control assets, telemetry, SCADA, and DER storage. Regulators can use the distribution system integration cost options (DISCO) to assess the costs of different DER integration options motivated by policy changes. LBNL work in reliability and resilience includes a meta-analysis on economic models of electricity supply interruption, best practices for estimating the cost of customer power interruptions and how to conduct studies on this topic, and a case study analysis focused on long-duration outages from extreme weather. See Appendix A for details.

3.2 Planning Functions

National laboratories have developed solutions to support building or microgrid operators in the optimal sizing and placement of BTM DERs. Examples of these tools include LBNL's Distributed Energy Resources Customer Adoption Model (DER-CAM), NREL's REopt and Sandia National Laboratories' (Sandia's) Microgrid Design Toolkit (MDT). These tools have been used in the past to support consumers, inform utility decisions around DER investments, and assess economic feasibility of microgrid deployments. NREL's PRECISE allows distribution planners to assess incoming DER applications with local grid conditions, and determine advanced inverter function settings (e.g. volt-VAR, volt-Watt) that will provide necessary control performance.

Other tools and frameworks focus on distribution grid expansion and planning efforts. IMT, an OE-supported modeling framework developed by LBNL, models individual consumers' behavior associated with DER adoption and integrates economic incentives (such as electricity rates) into the classic distribution network expansion and planning methodologies. An additional optimization modeling framework, Risk-controlled Expansion PlAnning with dIstributed Resources (REPAIR), develops reliability and resilience planning models to enable risk-controlled decisions in a utility's grid planning phase to prevent and mitigate the effects of outages caused by routine equipment failures or by high impact, low probability (HILP) events, such as storms, earthquakes, or wildfires.

DiTTo and CIMHub provide feeder model conversion tools. SMART-DS and the Distribution Grid Integration Unit Cost Database provide realistic feeder and cost data. GridLAB-D [15], OpenDSS [49] and PyDSS provide access to powerflow tools for planning. The dsgrid tool can estimate loads, while dGen can estimate DER adoption. EMerGE estimates DER impacts on the distribution grid. REopt and SAM can emulate the planning processes that DER stakeholders would follow. See Appendix A for more information on these.

3.3 Design Functions

Distribution system design functions use many of the same tools and data sets as planning and operational functions. One of the main differences is the time horizon of interest. Planning functions may focus on time horizons at least one year away—often longer. Operational functions focus on real-time analysis and state estimation, but may look a few days ahead, such as when planning service restoration during extreme events. Design functions have time horizons in between. For example, a designer might need to specify new voltage control settings to solve an operational problem within a few days. In another example, the designer might be specifying system upgrades, protective relays, or voltage control settings for a new DER installation that will be commissioned in nine months. Power-flow and short-circuit analysis are the basic tools, as they are for many operational and planning functions. As far as possible, planning, operational, and design functions need to use consistent system models to obtain consistent results.

There are some indicative differences between design functions and the other two:

- Design functions include setting control and protection device parameters, which may be adaptive settings. Operational functions include control and protection system performance. The operators choose between setting groups and modes, but would not re-engineer settings during operations.

- Design functions may include feeder sectionalizing, i.e., the placement of switches and communication systems for optimization and outage restoration. The operational functions can use these switches, but not place new ones.

- Planning functions may determine the need for additional capacity at a location, choosing the voltage level, transformer size, and meter location. Much distribution planning can be done with balanced three-phase models. Design functions take over with more detailed per-phase modeling and specific equipment selection, protection, and voltage control.

- DER interconnection and system impact studies are generally design functions at the utility. The study outputs include specifications and parameter values for control, protection, and metering.

- Specialized tools like EMTs and harmonic analysis may appear in design studies, but rarely in planning or operation studies. These tools are not commonly used on distribution systems, except to investigate equipment failures or power quality problems, and to design mitigation. For DER integration, EMT and harmonic tools may be necessary to simulate grid-forming inverters and frequency excursions, or investigate algorithms that work on waveform data.

- Vendor-specific equipment data are more important in design functions than in planning or operations. For example, protection engineers generally want to use the specific fuse curves and relay settings files to perform analyses. In the final design, conductor, cable, pole, duct, and transformer types will have been selected to replace the typical data from a planning study.

- System models for design tend to be the most detailed. Operational models could have the same level of detail, but utilities often use simpler models with just SCADA points. Planning models can be detailed, too, but since phase unbalances and future growth are uncertain, a model is often simplified. Planning models may also use longer time steps, with less detail required in the control and protection data.

Feeder model conversion tools include DiTTo and the CIMHub module of GridAPPS-D. Both are open-source. These tools allow a researcher to convert detailed feeder models from a utility partner into one of the research-grade tools like GridLAB-D or OpenDSS. This capability addresses the requirement for more detailed system and equipment data to perform realistic design studies. Converting the utility's model into the format of the tool, and validating the result, may require manual intervention.

The laboratories do not currently have open-source tools that are suitable for EMT or harmonic analysis. When needed, they license a commercial tool like Power System Computer Aided Design (PSCAD) or Electromagnetic Transients Program, or they can use Alternate Transients Program (ATP). Each of those requires a model conversion, if the utility partner does not already have an EMT model prepared in the same tool. This can be a barrier to use of EMT in research projects, where it may be important for inverter-based resources. GridLAB-D now has a fast-phasor analysis, which is akin to unbalanced dynamic simulation, but is not a true EMT simulation.

Research staff at the laboratories do not always have practical design experience on electric power systems. Whenever the design question can be formulated as an optimization problem with well-defined metrics, the laboratory researchers can solve it readily. Voltage control and volt-var optimization fall into this category. Whenever the design question calls for more practical experience, the laboratories often rely on utility advisors. Protection system design falls into this category. The laboratories have the basic tools to calculate fault currents and relay operating times, but often lack the experience to design and validate a complete protection scheme for the feeder. Protection is one of a utility's most important concerns at the design stage of DER interconnection. At the planning stage, it may be assumed that protection issues can be solved later, and at the operational stage, the protection issues have already been solved. The laboratories do not appear to have specific capabilities in protection system design.

3.4 Operational Functions

Operations analysis is important for evaluation, assessment, and deployment of new operating regimes for DERs and network assets. Operations analysis can also effectively assess the effects of DER integration and help inform planning and design decisions for successful integration. Modeling and simulation test beds with co-simulation are required for operation analysis, including DER device and component models, modeling communications infrastructure, and network load flows. HELICS is a proven co-simulation architecture for this purpose. Control and aggregation of DERs should be possible through such communication infrastructures to assess the effectiveness of control regimes for decentralized, centralized, distributed, and hierarchical control architectures.

In the network domain, tools that can model load-flow operations have been used, such as GridLAB-D, OpenDSS, and PyDSS (Python interface for OpenDSS). These load-flow engines can model DER device operation such as inverter controls, and are typically used for quasi-static time-series simulations. Device operational models can be used to represent DER in power flow (e.g., for solar PV, battery energy storage). On the demand-side, EnergyPlus^{TM} [50], including ResStock and ComStock, and more recently Object-oriented Controllable High-resolution Residential Energy (OCHRE), have been used to generate end-use demand profiles, and EVI-Pro has been used to capture EV charging patterns.

There are key challenges related to control and operations. Several aspects need to be designed and optimized for widespread control and harmonization of grid assets and DERs controls: the overall control and communications architecture, scalability of the problem (e.g., for aggregating thousands of DERs), sensing and measurement of diverse grid signals, interoperability of devices, communications infrastructure, and cybersecurity sensing.

There is also a great need for PHIL experimental setups, allowing device characterization within a wider simulated real-time network. Grid control solutions, such as ADMS and DERMS, and test beds for them, are essential for their development and validation. Advanced control frameworks that move to real-time operations and integration of grid assets and DER operation, e.g., real-time optimal power flow (RT-OPF), are also of key research interest.

Operational function research also includes protection and cybersecurity. Being able to model transient network phenomena for DER and network responses to contingencies and faults is essential for helping design new protection schemes that take into account power injections at the grid edge. Cybersecurity operations are becoming essential as more diverse DERs with enabled remote communications and control capabilities are incorporated. Malicious control of DERs poses a threat to overall network security, and examining the potential threats and solutions for their mitigation spans multiple domains and requires sophisticated co-simulation capabilities. Idaho National Laboratory and PNNL are currently performing a Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL) project to improve the cybersecurity of distributed wind generation. MIRACL is funded by WETO.

An operational/design simulation framework would support:

- Development of custom DER control algorithms and embedding them into the power system simulation environment.

- Solving real-time optimal power flow problems at the grid edge and optimizing power flow between devices, helping new DERs work for the grid and the grid work for DERs.
- Development of building-to-grid co-simulation platforms for a controllable high-resolution residential and commercial energy model comprising DERs and DSM.
- Emulating distribution networks with DERs and vulnerability analysis with cyberattack scenarios.

For developing interoperable distributed applications, the GMLC project GridAPPS-D provides a platform and test bed that includes HELICS, GridLAB-D, OpenDSS, and OCHRE, with EnergyPlus and ns-3 support being added. The platform provides an application program interface (API) that emphasizes standards like the IEC CIM, OpenFMB (Open Field Message Bus), and DNP3. The platform with applications can run in a Docker container, or from cloud computers. Online documentation and Python-based training notebooks have been published for GridAPPS-D. PNNL and NREL have collaborated on GridAPPS-D, and developed sample applications for it.

3.5 Analytical Domains

Analytical capabilities of national laboratories enable creation of tools, models, and techniques that assist in the planning, design, regulation, and operational functions discussed above. Some of the key analytical capabilities are listed here:

- Temporal: National laboratories offer a substantial set of tools that model and solve DER problems over a wide temporal range. For steady-state power flow and time-series simulations, GridLAB-D and OpenDSS have been widely used as distribution system simulators. The steady-state simulators can model DER operation and simulate basic controls such as inverter controls. For advanced controls such as volt-var optimization and other ADMS applications, GridAPPS-D modules are available, with further updates coming down the line. Though GridLAB-D can be used for unbalanced dynamic simulations, currently no laboratory tool is available for transient simulations.

- Economics: Modeling and analysis of DER adoption scenarios and associated costs is important for utility grid planning and expansion. In particular, finding the optimal size, location, and dispatch of DERs from the utility's and customers' perspectives is critical for planning ranging from several months to several years. In this space, tools such as DER-CAM, Distributed Generation Market Demand (dGen), DISCO, and IMT provide DER adoption modeling and subsequent economic planning capabilities such as utility rate design and optimal DER investments. The ICE Calculator estimates the value of reliability improvements for planning. To model transactive markets for DER, Transactive Energy Simulation Platform (TESP) is available for creation of new market mechanisms, price discovery, and decentralized (consensus) mechanisms [51].
- Spatial: The distribution system must be modeled and solved at spatial levels ranging from the component/grid-edge devices to the substation/distribution service territory that affects the bulk system. The detailed thermal, physical, and electrical properties of these components should be modeled to closely approximate the characteristics of real-world systems. For this purpose, GridLAB-D and OpenDSS can model a wide array of components. Despite their

modeling capabilities, often the simulators are limited by the fact that real network data sets are typically restricted and thus not readily available. To this end, synthetic feeders and data sets are required that replicate real distribution feeders in terms of complexity, structure, and detail. SMART-DS (Synthetic Models for Advanced, Realistic Testing: Distribution Systems and Scenarios) offers a library of highly detailed synthetic feeders that can be used in a variety of DER integration studies. Similarly, dsgrid can create detailed electricity load data sets to model realistic demand. Also, EMeRGE (Emerging technologies Management and Risk evaluation on distribution Grids Evolution) can generate feeder models from geographic information system (GIS) data.

- Devices and DERs: Along with spatiotemporal grid modeling and analysis, DER modeling and optimization pave the way for detailed DER integration studies. A DER may belong to the generation, storage, or demand-side subclass, where each subclass contains diverse DERs. Many utilities still consider aggregated, simplified DER models and do not consider the specifics of each DER technology. Thus, it becomes difficult to capture the effects of diverse DERs when oversimple models are used. To this end, tools such as PREconfiguring and Controlling Inverter SEt-points (PRECISE) compute the optimal inverter settings (i.e., volt-var, volt-watt) for distributed solar PV via mathematical optimization. Similarly, NREL's System Advisor Model (SAM) can model different types of DERs such as solar PV, battery storage, or wind power while enabling a detailed technoeconomic analysis for each DER. Building energy modeling tools such as EnergyPlus and OCHRE enable detailed modeling of demand-side resources, such as flexible loads like heating, ventilating, and air conditioning (HVAC) and water heaters. REopt formulates an optimal mix of generation technologies for an energy management system. Another tool, RT-OPF, optimizes power flow problems at the grid-edge or DER level.

- Connecting Infrastructures: To capture the interactions among connecting infrastructure, HELICS was developed by teams at several national laboratories. It is used for co-simulating with multi-domain simulators, such as MATPOWER for transmission and GridLAB-D for distribution. Similarly, the transport network can be modeled in Behavior, Energy, Autonomy, and Mobility (BEAM), which was developed by LBNL. It can be co-simulated with GridLAB-D via HELICS to capture the effects of EV charging on the grid. Simulators like ns-3 that model the communication network can also be co-simulated using HELICS. In fact, any tool can be co-simulated using HELICS, because its interface code is open-source. This opens a vast array of opportunities to model and solve multi-domain systems. Moreover, some tools can optimize specific connecting infrastructures, such as REopt, which optimizes the energy and water nexus.

4.0 Analytical Gaps and Research Roadmap

Compiling the requirements, research questions, and existing capabilities, this section recommends a roadmap to address the gaps in three general stages:

1. Develop a common results-delivery platform to be shared among all roadmap projects and updated annually. Each EERE technology office may contribute a reference DER model for holistic analyses. This project could begin six months before the others.
2. Initiate a series of short-term research projects to deliver benefits within a few years. The projects could address utility planning, design, operations, and analytical tools that would be needed for more DER interconnections. These projects could also be useful if other resources outpace DER, i.e., the projects carry low regret.
3. Initiate a series of longer-term research projects to deliver benefits in five to ten years. The topics could include new grid architectures, new regulatory frameworks, multi-sector electrification, and other transformations needed to support potential extensive DER adoption.

4.1 Open and Multi-Domain Modeling Platform

MATPOWER has a ”critical mass” in the bulk system analysis research community, with about 250,000 downloads, which encourages use of MATPOWER over alternative open-source tools that may have the same capability. In turn, that fosters replicability and lowers the cost of research tasks that are built upon MATPOWER. In the distribution system analysis community, GridLAB-D and OpenDSS each have around 100,000 downloads. EnergyPlus updates each have around 40,000 downloads in the building analysis community. This part of the roadmap aims to achieve similar critical mass in open-source modeling for flexible system designs. The scope expands to economics, communication systems, human behavior, vehicles, industrial processes, and other DER technologies.

Distribution analysts should strive to use co-simulation to incorporate the best-in-class models in associated domains to allow for holistic, integrated analysis. To achieve this, some customization will be needed. One such example is EnergyPlus, which is widely seen as the best-in-class modeling and simulation tool for heating and cooling and energy efficiency analysis in buildings. The EnergyPlus platform is ideally suited for capturing the thermal and physical elements of buildings that drive heating and cooling energy consumption. However, the platform is not an electric load model (i.e., dealing with active and reactive power, voltage dependences, dynamic motor models of HVAC equipment, etc.), and hence needs customization. Alternatively, there are thermal-electrical models being used in the research world (e.g., GridLAB-D) that have excellent load models but substandard (compared to EnergyPlus) thermal and physical modeling of the building envelope.

Long-term planning and technoeconomic analysis could use different models. Existing distribution system technoeconomic models in the DOE space include microgrid design tools (such as DER-CAM, REopt and Microgrid Design Toolkit) as well as distribution grid investment and planning models such as REPAIR and IMT. These models can capture the value of DERs in both blue sky (day-to-day) and black-sky (crisis) scenarios and provide optimal portfolios of investments to utilities and BTM prosumers. However, these optimization models are limited in terms of computational burden: they can only be applied to systems with a relatively small number of nodes and they neglect important aspects of intraday operational DER economics that are becoming more important with extensive penetration of solar and storage technologies.

At the same time, as uncertainty becomes a key aspect of distribution system economics, DER valuation methodologies need to be updated to account for the stochastic nature of DER operations and to capture the value of dispatchable DER assets (such as storage) in mitigating operational and economic risks. Thus, a roadmap for the next generation of distribution grid technoeconomic models should include:

- Addressing the dimensionality of technoeconomic optimization models: When including uncertainty and real-size distribution grids, these models grow exponentially with the number of nodes in the system and with the number of scenarios of renewable generation, states associated with grid failures, and combinations of outage events. Therefore, tailor-made decomposition methods as well as innovative approaches to address dimensionality of these models (for example based on machine learning and graph-theory analysis of distribution networks) are needed.

- Capturing economic and operational risks in DER valuation: The value of DERs (in particular PV technologies) has been quantified in multiple forms, capturing different streams of value to the grid, such as the ability to decrease energy costs, defer investment, reduce losses and, when combined with storage, participate in energy arbitrage and ancillary services. In state-of-the-art valuation methodologies, DER values to the utility are captured as deterministic or expected costs. However, the effect of these DERs on the overall uncertainty of the system entails, by itself, a (positive or negative) value that current valuation methodologies do not capture. This value is purely risk based; it corresponds to the contribution of the DER technologies to the overall uncertainty of the system. It is translated into additional grid investment/operational costs or savings. Thus, risk-based methods are needed to quantify the DER contribution to distribution grid economics.

- Capturing interactions between models and agents in the same system: For example, when multiple DERs compete in the same energy and grid-services markets, their decisions will influence each other through their connections to the same grid and market. Both expected value and risk metrics could be affected, and lead to underperformance in the real world. Reinforcement learning and other new behavioral modeling techniques may help.

This modeling platform integrates the domain and technology simulators through a common API and HELICS messaging bus, shown in Figure 8. Developers of a DER technology model must define ”domain ports” that enforce laws of physics, (e.g., conservation of energy, conservation of charge) at the terminals. All of them will have at least one electrical port for the grid interface, which must enforce Kirchhoff’s Laws for the through variable (current) and across variable (voltage). If the device has a thermal interface, then it must have a port with heat flow as the through variable and temperature as the across variable. Similar conserving port definitions apply to other domains like hydraulic, translational mechanical and rotational mechanical. These conserving domain ports are more fully described with Modelica, Matlab/SimScape, and in textbooks [52, 53]. The DER technology model may also have non-conserving interfaces to data for weather, finance, human behavior, etc. The virtual battery concept may also be useful in describing a DER technology’s ability to supply or absorb energy and power [54].

On the left-hand side of Figure 8, various domain and system simulators interface to each other via the API and/or HELICS. In a research project, developers could add their own code (usually written in Python) to interface with the whole suite, adding some functionality under investigation. The modeling platform should also have a means of support, such as annual developer workshops, and regular web-based office hours.

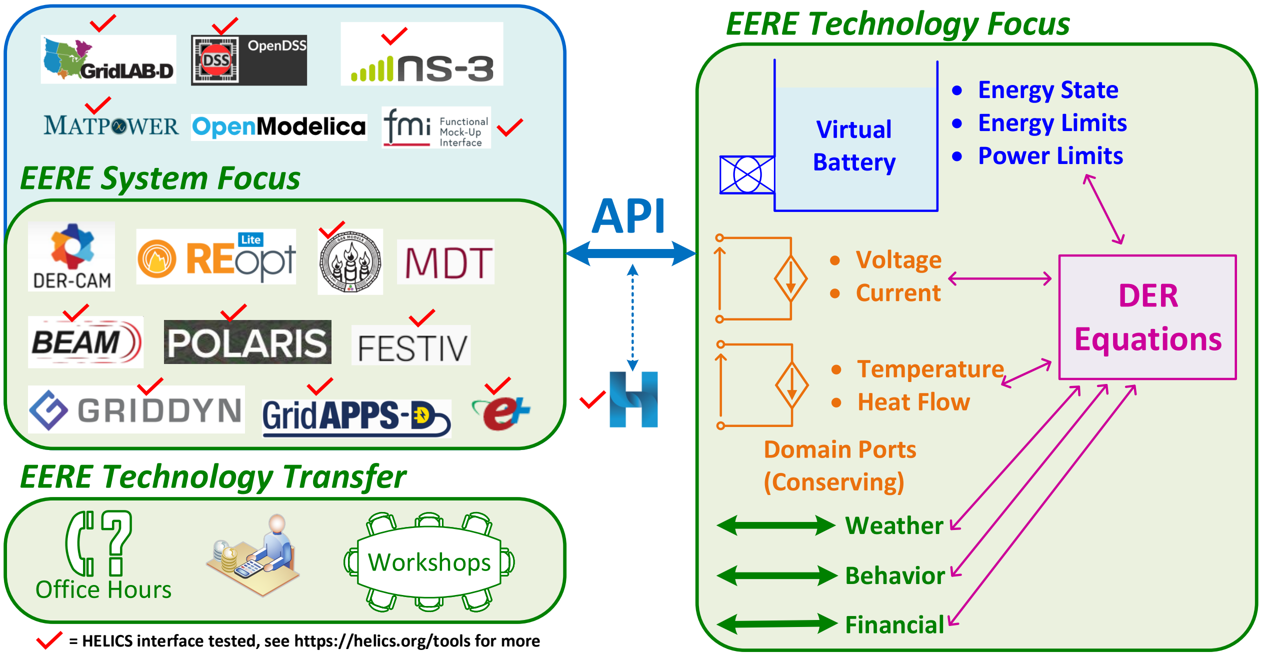

Figure 8. DER technology models interface with the distribution system through an API designed to work with HELICS.

4.2 Data Gaps and Interoperability

Researchers often have trouble finding realistic data, test cases, and reference algorithms in other domains that touch on their own. Having less experience, they may choose test cases and methods that no longer represent best practice in the other domain. This part of the roadmap aims to identify sources and standards for data that can be used to better support cross-domain research projects.

For example, the IEC CIM standard (IEC 61970-301) can be used to exchange power system models, and the IEEE C37.111 standard (COMTRADE) can be used to exchange power system measurement data. Using standards involves a learning curve, but standards facilitate adoption of a successful research project's results. EERE could provide interoperability tools and specify protocols that help researchers adopt standards. Use of HELICS as a co-simulation framework, especially among the DOE laboratories, should be encouraged. Use of any other co-simulation platform would increase project costs and pose a barrier to adoption of project results by others. The roadmap should incorporate other appropriate standards identified for buildings, vehicles, power electronics models, etc.

4.3 Distribution Planning and Design Use Cases with DER

Integration of a myriad of DERs, both existing and emerging, into the distribution system is still a major challenge. Information on the potential adoption levels, the timing of adoption, the consumption/production profiles of DERs, their technical response, and their potential positive or negative effects are all required to adequately plan and design the network. Interconnection standards or pricing mechanisms that may change the adoption and operation of DERs will also require this information. Figure 9 shows how DER offers new options to achieve grid reliability and resilience, although these new options complicate planning and design. Figure 10 shows how DER hosting capacity may be increased with DER adaptations, i.e., business as usual (BAU) for today, or with adaptations in the distribution network (DN). Distribution utilities can use two approaches to DER integration, or a mix of these approaches, to optimize the total cost of hosting capacity.

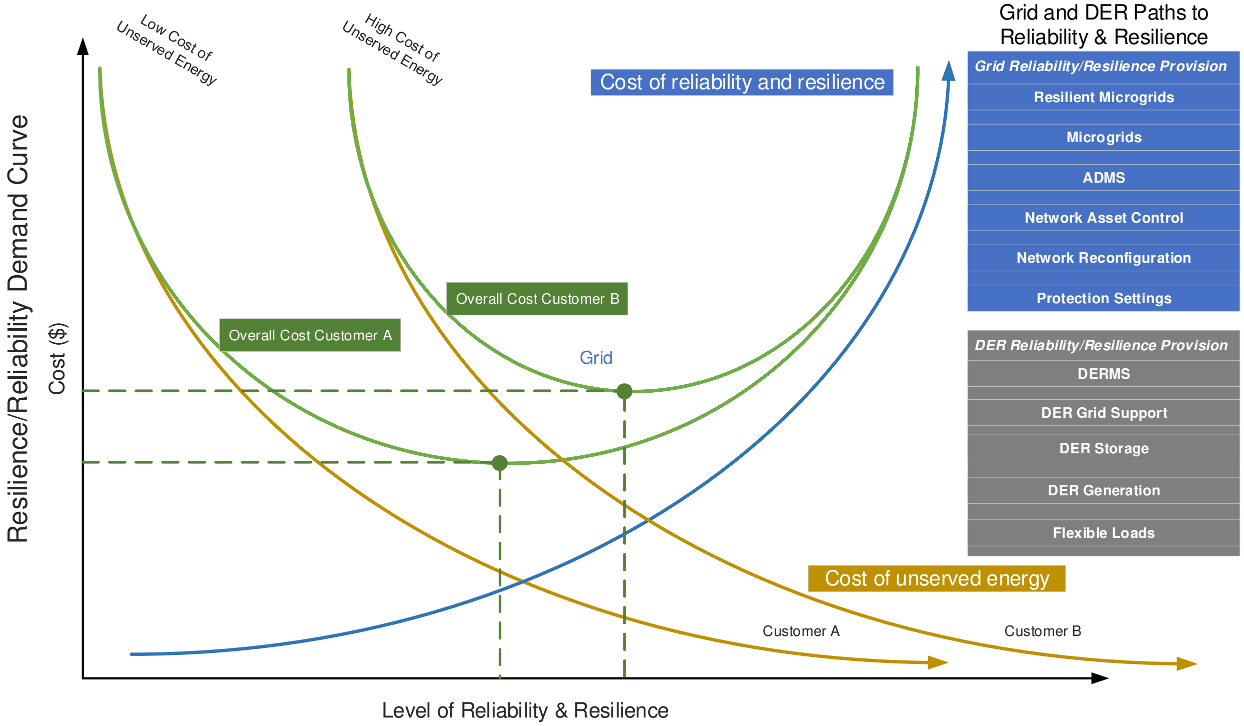

Figure 9. DER offers more design options to provide grid reliability and resilience.

4.3.1 Adapting DERs to Grid Conditions

This approach to DER integration would involve more applied research, more DER limitations and requirements, and piecemeal changes to accommodate more DERs. The approach would emphasize minimizing grid-side costs, by minimizing changes to grid infrastructure, operations and processes. It is an extension of BAU, but cost minimization and industry engagement is still required to change present practices. Examples of this approach may include:

- Continually revise IEEE 1547-2018, UL1741, California's Rule 21, Hawaii's Rule 14H and other standards or policies.
- Continue the first-come, first-serve approach of most existing DER interconnection processes.
- Continue the practice of limiting DER hosting capacity, although incremental changes are still possible from the result of applied research projects.

Each of these items needs to consider:

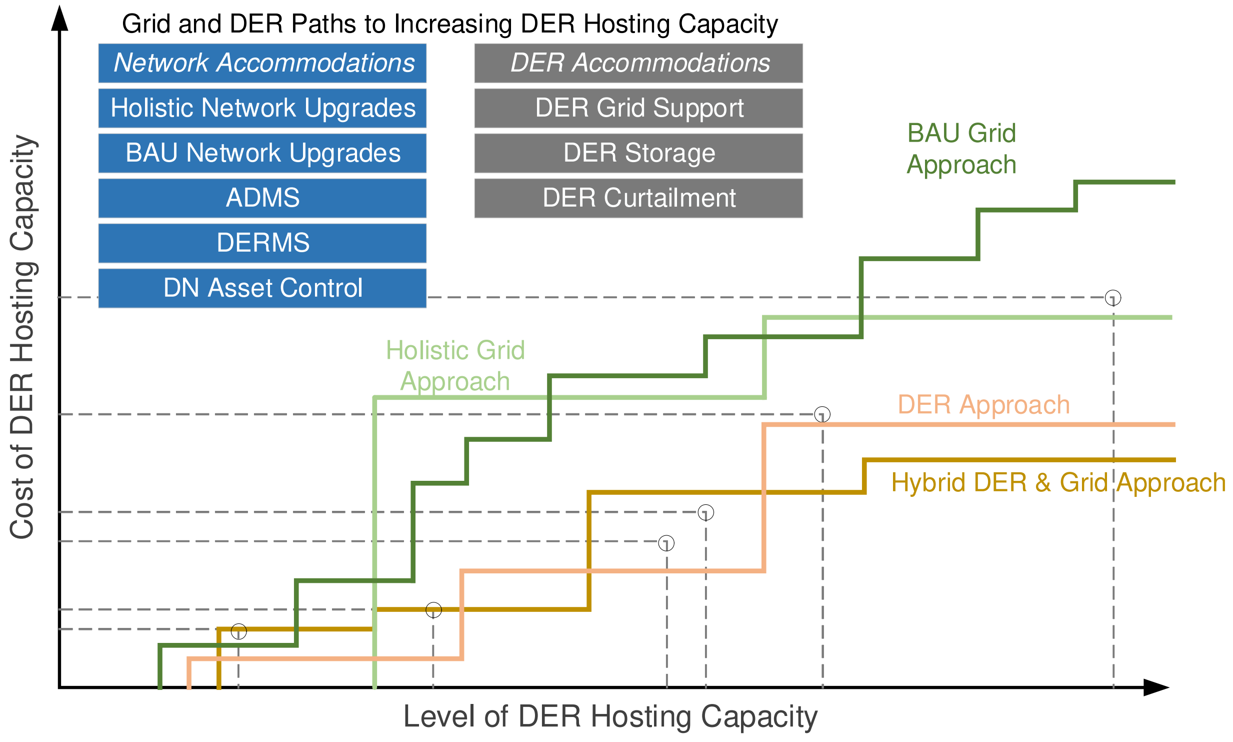

Figure 10. DER hosting capacity may be increased at less cost than business as usual (BAU) by mixing DER, distribution network (DN), and holistic accommodations.

- Reliability and resilience, including the effect of interconnection standards and protection design practices.
- Control and protection, including the effect of communications and centralized vs. distributed control architectures.
- Markets and tariff structures, including the effects of aggregation.
- What is the opportunity cost, if any, of less decarbonization?

4.3.2 Flexible Grid Planning and Design

This approach to DER integration would involve more basic research to redesign the grid, establish new markets, and create new processes that enable much more use of DER than by extending BAU. New analysis capabilities can support development and evaluation of new distribution system design concepts, such as fractal AC microgrids and medium-voltage DC, to achieve better efficiency and resilience. FEMP and WIP can use these design tools and products to support new federal, state, and municipal power systems. Other offices in EERE can use the tools and products to inform research efforts and especially field demonstrations.

Some of the re-design options include:

- Secondary networks could be re-designed to allow reverse power flow, which would enable much more DER to connect in downtown urban areas. As shown in Figure 11, these networks currently achieve high reliability by setting the network protectors (NWP)s to a sensitive trip on reverse flow. With a primary fault in the location shown, the green circuit breaker trips on overcurrent and the two highlighted green NWPs trip on reverse power flow to the fault. The fault is quickly isolated and the building loads are undisturbed. In this design, DER cannot export from the network. Utilities allow only small amounts of DER, i.e., a level called *de minimus* in IEEE Standards [55]. New designs with communications, adaptive settings and new NWPs could allow more DER in the network, without compromising reliability of service.

- Transactive systems and other retail market structures may have the potential to increase DER adoption, by opening the benefits to a much larger group of stakeholders. Besides changes in policies and tariffs, a transactive system would require investments in communications, large-scale real-time markets, and distributed control for the grid, as well as prosumers.

- Medium-voltage DC systems, shown in Figure 12 (left), could be interfaced with existing medium-voltage AC feeders. The blue portion is DC, interconnecting storage, PV, a fuel cell, and an EV charger, all of which are naturally DC-coupled. Existing motor loads, lighting loads and plug loads could remain AC-coupled, with some transition to DC-coupled occurring over time. The hybrid design may be more efficient and flexible, considering that each DC system forms a natural microgrid.

- Networks of AC microgrids, shown in Figure 12 (right), allow DER to provide more flexibility and resilience through islanding. In this example, an 8500-node IEEE test feeder, which came from a real utility feeder, has been converted to a more flexible set of three sub-feeders. With additional DER, switches, substation source connections, and distributed intelligence, the new circuit can be switched into different radial, meshed or island configurations. The protection and control settings adapt to each configuration, with a benefit of more operating flexibility, and more resilience to possible loss of bulk system connections at the substations.

4.3.3 Economic Distribution Grid Planning with DERs

Utilities have started doing more advanced distribution system planning to gain a clearer view of their territory and optimize grid investments to meet reliability standards and reduce costs. New technology and an increase in customer-sited resources have transformed the edges of distribution systems; customers are no longer seen as passive loads with predictable load curves and growth projections. Instead, consumer-side decisions (e.g., how they may choose to adopt or operate DERs) can change net load characteristics at the feeder level, which affects the needs for network reinforcement and utility investment. In some cases, net load alteration by DERs may weaken reliability, whereas in other cases, DERs may provide value. Without a better understanding of DER adoption patterns and effects, utilities may face operational issues or may spend unnecessary capital for services that existing DERs could provide (especially for dispatchable DERs such as demand response or battery storage). Better planning and forecasting would help mitigate both unnecessary expenditures and reliability issues. Over recent decades, distribution utilities have forecasted these net loads in a top-down manner across large groups of customers and have focused investment on traditional resources to generate and/or deliver power to meet demand and reliability standards. However, these traditional forms of top-down econometric forecasting do not account for location-specific constraints or operational risks on specific circuits. Also, these long-term demand forecasts cannot capture new DER adoption patterns or assess the effects of deployment, intraday variability, and dispatch of BTM DERs during grid planning. Therefore, bottom-up methodologies and approaches to better integrate DERs into grid planning are needed:

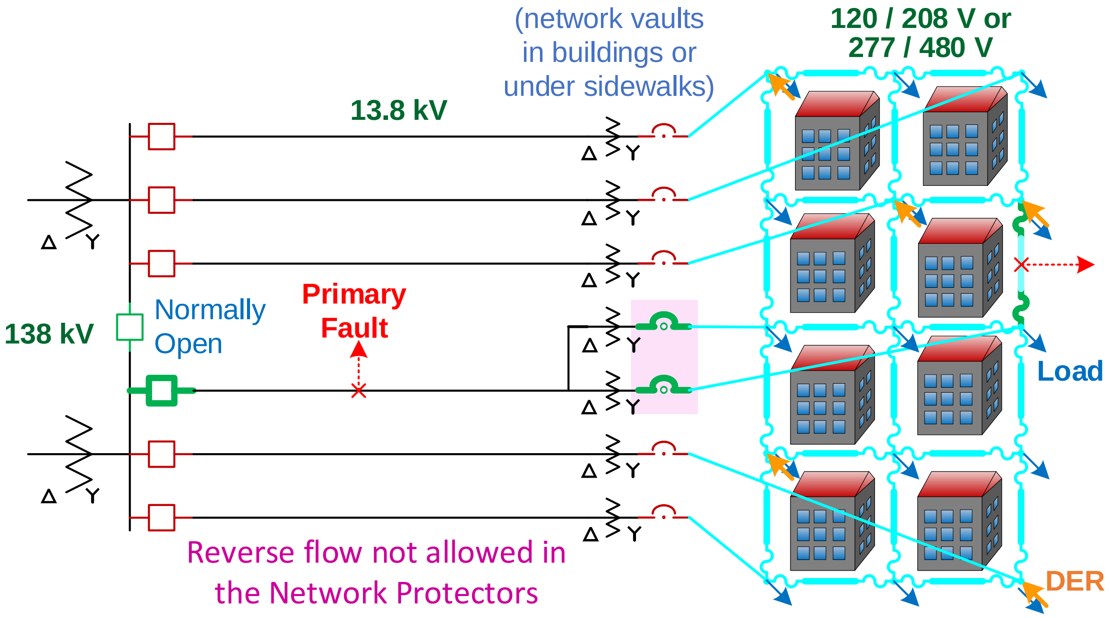

Figure 11. To support reliability, many secondary networks in urban areas allow only minimal DER connections.

Figure 12. New designs adapt radial AC circuits to offer more flexible options for DERs and resilience.

- Capturing DER integration during grid planning. This would require understanding the costs and benefits of each utility intervention or measure (e.g., non-wires alternatives, dynamic pricing, smart EV charging). Understanding how these interventions affect distribution system needs will be important for least-cost DER integration and grid planning. Better DER visibility and consideration in a utility's planning phase could identify both risks and value of investment deferral, loss reduction, resilience, and reliability.

- Analysis that can quantify distribution system benefits specifically from energy efficiency and demand response. This should build on prior work that has emphasized the time-dependent value of energy efficiency and demand response based on hourly utility system costs at the generation and transmission system levels. The new objective is to characterize the value of energy efficiency and demand response on representative distribution feeders and the consequent effects on investment planning and integration strategies to address distribution system constraints.

- Methods and analyses that can address long-term uncertainty associated with DER adoption patterns and capture the consequent risk for distribution system planning. This includes understanding how utility investments in control and flexibility solutions (for example, storage and microgrids) can work as hedging against the uncertainty of renewable distributed generation. Further analysis should investigate the role of distribution grid investments in mitigating the upstream uncertainty (e.g., transmission system), reducing the exposure of the bulk power system to uncertainties of renewable-based DER penetration.

4.4 Grid Policy, Regulatory, and Valuation Methods to Improve DER Integration

Net-metering tariffs have been a main driver of BTM PV adoption. However, many states are shifting from net metering toward tariffs that better align with system value as PV costs have declined and concerns over cost shifting have intensified. Without alignment between incentive levels and actual DER value, uncontrolled adoption and operation of DERs can lead to significant grid hosting capacity costs, which may trigger new energy equity challenges among consumers and prosumers. Some studies [56] have shown that poorly designed utility pricing programs can lead to zero or even negative benefits to the grid. Thus, rates and programs that account for temporal and/or locational system value are crucial to reduce system costs related to DER integration. Proper design could yield more beneficial DER adoption and/or operation and open up additional value streams for prosumers while reducing the overall system costs. Therefore, important research activities include identifying existing barriers to better alignment of DER prices and programs with distribution grid costs and values. Additional research activities could go further, to capture the interplay between DER adoption, distribution effects, and rate design. Four examples of initial research activities are listed here:

- Review utility proposals for distributed storage, including the assumptions, methodologies, justifications, and documentation that regulated utilities have filed with state PUCs for proposed distributed storage programs and pilots intended to advance demand flexibility. It is also important to assess the considerations that PUCs are applying in their review of these proposals as well as the trends and challenges of establishing these programs.

- Summarize the experience to date of utility pricing and programs that seek to provide distribution grid services, including an assessment of enrollment, performance, and cost trends. These summaries may also yield understanding of whether and how utilities are aligning prices with services not traditionally valued at the customer level (e.g., wholesale market services, internal costs like volt/var, power factor correction, etc.).

- Quantify DER costs and benefits on the distribution system from implementing specific programs and/or rates. Specifically, how retail rate design may affect both the adoption and operation of DERs, and the resulting costs and benefits to the distribution system.
- Assess alternative business models that could better align incentives for utilities to pursue DERs in support of distribution system services. This could include incremental approaches, such as performance incentive mechanisms or requirements to identify cases where non-wires alternatives are viable. More comprehensive approaches could fundamentally alter the approach to setting returns on equity, including tiered performance incentive mechanisms.

Furthermore, electrification of important sectors of the economy and society (government, health, information, industry, etc.) has made power distribution vital for communities' life and safety, requiring the grid to be reliable and resilient. The operational uncertainty of variable renewable DERs, together with HILP events such as wildfires, floods, or hurricanes, can entail a new risk to the distribution grid's reliability and resilience. Dispatchable DERs and options for their configuration (e.g., microgrids, backup storage investments) can be a way to manage this uncertainty. Nevertheless, DERs' economic reliability and resilience values have not been quantified within a specific analytical framework. On this topic, the main policy and analysis research gaps are threefold:

- A DER resilience analysis to determine the ability of DER technologies to improve distribution system resilience in four dimensions: (1) reduce the magnitude of disruption, (2) extend the duration of resistance, (3) reduce the duration of disruption, and (4) reduce the duration of recovery. The analysis should apply a consistent perspective, framework, and approach to modeling the sequence of events and their effects. Probabilistic simulation methods across various grid topologies with and without DERs are needed to compare costs, values, and key reliability and resilience performance measures.
- Economically efficient incentives for various DER deployments that reflect their ability to increase resilience across electric utility customer classes. It is important to study the distribution of resilience benefits across different socioeconomic groups and investigate equity aspects of resilience costs and benefits across consumers.
- A new framework to design reliability metrics that recognize the reliability value of DERs from the customer perspective and the value their services bring to the whole power system. Widely used reliability metrics such as SAIDI and SAIFI are not suited to describing the customer's reliability experience and do not capture the value that DERs create, for customers or for system reliability. Traditional reliability metrics focus on loss of load but do not reflect the loss of services that DERs provide to the system through demand response, frequency regulation, and other ancillary services. Without these metrics, state regulators, utility planners, and policy makers cannot design policies that recognize the value of DERs to compensate for their operation and incentivize their deployment.

Finally, policies have changed recently to reduce barriers to DER participation in grid services, opening additional value streams. In parallel, the emergence of new standards and technology has increased DER controllability and communication, making it more feasible to provide services with short notice. However, some barriers to implementation remain as the industry works to better understand the capabilities, values, and risks associated with replacing incumbent technology with DERs. These include internal processes to quantify territory-specific DER grid value, coordinate between grid levels (e.g., customer, distribution utility, and transmission operator), collect and use more granular data, and integrate new policies and rules. Only recently have the policies, hardware, software, and adoption levels reached the point at which better communication, control, and coordination of DERs could offer sizable benefits in grid operation and alignment with policy targets. Research could focus on activities such as better understanding how states or utilities make use of these new DER capabilities via programs, interconnection agreements, and the like:

- Examine which utilities/territories are using smart inverter capabilities and report the main challenges and best practices. Research on this topic could focus on practices that allow adoption of more DERs while still supporting reliable operation of the grid. Economic efficiencies may result from using DERs for distribution services where traditional infrastructure upgrades would otherwise be necessary.
- Examine how distributed battery storage can provide real-time balancing for either (1) A colocated distributed PV system or (2) A constrained, unbalanced, or otherwise weak distribution system via utility programs or interconnection agreements. This may look into the hardware and software capabilities necessary as well as any trade-offs that must be considered.
- Examine how DERs may be able to operate across different grid levels, such as among transmission operators, distribution operators, and consumers or aggregators. It will be important to understand the benefits and risks associated with dual participation and how it may affect each grid level separately. For example, how may a program or terms of participation be structured such that providing services at one level will not create reliability or economic issues on the other? What communication procedures will be necessary to support overall system reliability?

In Section 5.0, an example set of action items is outlined to implement this roadmap.

5.0 Next Steps

Having identified the needs for DER integration research, this section presents an example action plan to address those needs. First, EERE could lay some internal foundation for continuing success in holistic DER research. These activities don't require external funding. We suggest that:

1. EERE could assign a home for continuing engagement with OE and GMLC, and for coordination among the EERE offices, to present a unified position on its interests in DER and distribution system research. This would ensure that the roadmap is updated, and that new opportunities for synergy are timely identified. Those synergies may arise between EERE and OE/GMLC, or between different EERE offices. The SA team could fill this role, as its predecessor, SPIA, initiated this roadmap project.

2. EERE should consider how to improve its engagement with industry, especially during and after projects. Consortia and other collaborative frameworks could help industry participate in research, provide cost share, and contribute in meetings with business competitors (i.e., as they do now in standard development organizations). For projects that don't move into the Technology Commercialization Fund, abrupt project termination can leave valuable tools and results stranded, with no easy way for industry to use them. From experience of the project team and external reviewers, these have all been barriers to industry collaboration. EERE might be able to work more closely with groups like EPRI and NRECA to improve this collaboration.

Second, EERE could initiate the Open and Multi-Domain Modeling Platform described in Section 4.1. This can be done via multi-lab collaboration to ensure that prior DOE investments are fully leveraged, and that the national laboratories will be able to maintain the platform. This project could specify the following requirements:

1. Incorporate HELICS, standard data sets (Appendix A.2), and interoperability standards (Section 4.2) in preference to any new developments of similar functionality.

2. The platform code and all new code components should be licensed open-source, preferably a BSD-style license. Existing open-source tools (Appendix A.1) should be incorporated, in preference to any new developments of similar functionality.

3. Each EERE technology office may provide a reference DER technology model for grid integration, and this model should respond appropriately to grid voltage and frequency. The model should perform well in simulations of, at minimum, one substation with all connected feeders and DER. It's expected that most, if not all, of these models would be new developments.

4. Documentation and ongoing support mechanisms (e.g., annual workshops, weekly office hours) should be established. EERE could identify a funding mechanism for continuing support, possibly shared by many offices.

5. The beta testers could include representation from FEMP, WIP, EPRI, NRECA, one or two other national laboratories (i.e., not from the development team), and one or two universities. After the beta test, a public rollout could be offered with hands-on training.

Third, and after the Open and Multi-Domain Modeling Platform project has begun, EERE could initiate a stage of one or more projects to address the short-term research questions, as summarized in Sections 4.3.1 and 4.3.3. With reference to the more detailed research questions, this project stage could include:

- All stability questions from Section 2.2.
- All variability questions from Section 2.3.
- All security questions from Section 2.4.
- All uncertainty questions from Section 2.5.
- All situational awareness questions from Section 2.6.
- Requirement to deliver any code, documentation and examples for annual updates of the Open and Multi-Domain Modeling Platform.

Fourth, EERE could initiate a stage of projects to address the long-term research questions, as summarized in Sections 4.3.2 and 4.4. It’s expected, but not required, that this project stage would launch after the first one. The only prerequisite is that the Open and Multi-Domain Modeling Platform should be underway. With reference to the more detailed research questions, this project stage could include:

- All multi-sector electrification questions from Section 2.7.
- All energy equity questions from Section 2.8
- All valuation questions from Section 2.9.
- All network re-design questions from Section 2.10.
- The EMT/harmonic solver and the ”huge” DER optimization solver from Section 2.11.5. The Office of Science might be interested in these topics, too.
- Requirement to deliver any code, documentation and examples for annual updates of the Open and Multi-Domain Modeling Platform.

This is one possible implementation path. At each stage, EERE may consult with OE and GMLC for coordination, and to identify any co-funding opportunities.

6.0 References

[1] IEEE. *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*. Piscataway, NJ, 2018.

[2] NERC. 900 MW fault induced solar photovoltaic resource interruption disturbance report. https://www.nerc.com/pa/rrm/ea/October%209%202017%20Canyon%202%20Fire%20Disturbance%20Report/900%20MW%20Solar%20Photovoltaic%20Resource%20Interruption%20Disturbance%20Report.pdf, 2018. [Online; accessed 17-March-2021].

[3] NERC. 1,200 MW fault induced solar photovoltaic resource interruption disturbance report. https://www.nerc.com/pa/rrm/ea/1200_MW_Fault_Induced_Solar_Photovoltaic_Resource_/1200_MW_Fault_Induced_Solar_Photovoltaic_Resource_Interruption_Final.pdf, 2017. [Online; accessed 17-March-2021].

[4] California Public Utilities Commission. Rule 21 interconnection. https://www.cpuc.ca.gov/rule21/, 2021.

[5] Hawaii Public Utilities Commission. Rule no. 14: Service connections and facilities on customer's premises. https://www.hawaiianelectric.com/Documents/my_account/rates/hawaiian_electric_rules/14.pdf, 2021.

[6] DOE. Energy storage grand challenge. https://www.energy.gov/energy-storage-grand-challenge/energy-storage-grand-challenge, 2021.

[7] DOE. 2020 seto peer review. https://www.energy.gov/eere/solar/2020-seto-peer-review, 2020.

[8] DOE. Solar energy technologies office multiyear program plan. https://www.energy.gov/eere/solar/articles/solar-energy-technologies-office-multi-year-program-plan, 2021.

[9] DOE. Powering the blue economy. https://www.energy.gov/eere/water/powering-blue-economy, 2021.

[10] DOE. H2@scale. https://www.energy.gov/eere/fuelcells/h2scale, 2021.

[11] Elizabeth Connelly, Michael Penev, Anelia Milbrandt, Billy Roberts, Nicholas Gilroy, and Marc Melaina. Resource assessment for hydrogen production. https://www.nrel.gov/docs/fy20osti/77198.pdf, 2020.

[12] Mark F Ruth, Paige Jadun, Nicholas Gilroy, Elizabeth Connelly, Richard Boardman, A J Simon, Amgad Elgowainy, and Jarett Zuboy. The technical and economic potential of the h2@scale concept within the United States. https://www.nrel.gov/docs/fy21osti/77610.pdf, 2020.

[13] U.S. Department of Energy. Flow battery systems manufacturing foa. https://eere-exchange.energy.gov/Default.aspx#FoaIdfe9c1382-3bf1-48c4-bfdb-8fabd798d342, 2021. [Online; accessed 16-August-2021].

[14] Jeffrey D. Taft. Grid architecture: A core discipline for grid modernization. *IEEE Power and Energy Magazine*, 17(5):18–28, 2019.

[15] David P. Chassin, Jason C. Fuller, and Ned Djilali. GridLAB-D: An Agent-Based Simulation Framework for Smart Grids. *Journal of Applied Mathematics*, 2014(SI07):1 – 12, 2014.

[16] BH Obama. Presidential policy directive 21: critical infrastructure security and resilience (ppd-21)[press release]. the white house, office of the press secretary, 2013.

[17] Pacific Northwest National Laboratory. Grid modernization: Metrics analysis (gmlc1.1) – resilience. https://gmlc.doe.gov/sites/default/files/resources/GMLC1.1_Vol3_Resilience.pdf, 2020. [Online; accessed 4-March-2021].

[18] UCTE. Final report of the investigation committee on the 28 september 2003 blackout in italy. https://eepublicdownloads.entsoe.eu/clean-documents/pre2015/publications/ce/otherreports/20040427_UCTE_IC_Final_report.pdf, 2004.

[19] G. Liang, S. R. Weller, J. Zhao, F. Luo, and Z. Y. Dong. The 2015 Ukraine Blackout: Implications for False Data Injection Attacks. *IEEE Transactions on Power Systems*, 32(4):3317–3318, 2017.

[20] US DOE Office of Electricity. Multiyear plan for energy sector cybersecurity. https://www.energy.gov/sites/prod/files/2018/05/f51/DOE%20Multiyear%20Plan%20for%20Energy%20Sector%20Cybersecurity%20_0.pdf, 2018.

[21] James Keller and B Kroposki. Understanding fault characteristics of inverter-based distributed energy resources. Technical report, National Renewable Energy Laboratory, Golden, CO (United States), 2010.

[22] US Department of Energy. About the grid modernization initiative. https://www.energy.gov/grid-modernization-initiative, 2021.

[23] 109th Congress. Energy policy act of 2005. https://www.govinfo.gov/content/pkg/PLAW-109publ58/pdf/PLAW-109publ58.pdf, 2005.

[24] 110th Congress. Energy independence and security act of 2007. https://www.congress.gov/110/plaws/publ140/PLAW-110publ140.pdf, 2007.

[25] Sigifredo Gonzalez, Nicholas Gurule, Matthew J Reno, and Jay Johnson. Fault current experimental results of photovoltaic inverters operating with grid-support functionality. In *2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC)(A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC)*, pages 1406–1411. IEEE, 2018.

[26] Lori Bird, Michael Milligan, and Debra Lew. Integrating variable renewable energy: Challenges and solutions. Technical report, National Renewable Energy Laboratory, Golden, CO (United States), 2013.

[27] Thomas E. McDermott, Rui Fan, Priya Thekkumparambath Mana, Bharat GNVSR Vyakaranam, Travis Smith, Joshua Hambrick, Zhi Li, and Arthur Barnes. Relaying for distribution and microgrids evolving from radial to bidirectional power flow. Technical Report PNNL-29145, Pacific Northwest National Laboratory, 9 2019.

[28] D. Tom Rizy and Paul Ohodnicki. Sensing and measurement technology roadmap - devices including communications and data analytics requirements. https://gmlc.doe.gov/sites/default/files/resources/GMLC%20Sensing%20%20Measurement%20Strategy%20Sensor%20Technology%20Roadmap%20Final%20Report.pdf, 2019. [Online; accessed 17-March-2021].

[29] Christopher R. DeRolph, Ryan A. McManamay, April M. Morton, and Sujithkumar Surendran Nair. City energysheds and renewable energy in the United States. *Nature Sustainability*, 2(5):412–420, 2019.

[30] Matteo Muratori, Colin Sheppard, Tim Lipman, Bryan Palmintier, N Panossian, P Jadun, R Waraich, R Desai, and A VonMeier. Grid-enhanced, mobility-integrated network infrastructures for extreme fast charging (gemini-xfc) - technical presentation. In *DOE Vehicle Technologies Office (VTO) Annual Merit Review*, 2020. [Online; accessed 17-March-2021].

[31] U.S. Department of Energy. Equity in energy booklet. https://www.energy.gov/sites/prod/files/2021/01/f82/Equity_in_Energy_Booklet_1_11.pdf, 2021. [Online; accessed 23-February-2021].

[32] California Energy Commission. Energy equity indicators tracking progress. https://www.energy.ca.gov/sites/default/files/2019-12/energy_equity_indicators_ada.pdf, 2018. [Online; accessed 23-February-2021].

[33] Jaquelin Cochran, Mackay Miller, Owen Zinaman, Michael Milligan, Doug Arent, Bryan Palmintier, Mark O'Malley, Simon Mueller, Eamonn Lannoye, Aidan Tuohy, et al. Flexibility in 21st century power systems. Technical Report NREL/TP-6A20-61721, National Renewable Energy Laboratory, Golden, CO (United States), 2014.

[34] IEEE. Blockchain-enabled transactive energy. https://blockchain.ieee.org/verticals/transactive-energy, 2021.

[35] MI Olken. Transactive energy: Everyone gets into the act. *IEEE Power & Energy Magazine*, 14(3):4–16, 2016.

[36] Srinivas Katipamula, Charles D Corbin, Jereme N Haack, He Hao, Woohyun Kim, Donna J Hostick, Bora A Akyol, Craig H Allwardt, Brandon J Carpenter, Sen Huang, et al. Transactive campus energy systems. Technical report, Pacific Northwest National Laboratory, Richland, WA (United States), 2017.

[37] Steven E Widergren, Donald J Hammerstrom, Qiuhua Huang, Karanjit Kalsi, Jianming Lian, Atefe Makhmalbaf, Thomas E McDermott, Deepak Sivaraman, Yingying Tang, Arun Veeramany, et al. Transactive systems simulation and valuation platform trial analysis. Technical report, Pacific Northwest National Laboratory, Richland, WA (United States), 2017.

[38] David Holmberg, Martin Burns, Steven Bushby, Tom McDermott, Yingying Tang, Qiuhua Huang, Annabelle Pratt, Mark Ruth, Yogesh Bichpuriya, Narayanan Rajagopal, et al. NIST transactive energy modeling and simulation challenge phase ii final report. Technical Report Special Publication 1900-603, National Institute of Standards and Technology, Gaithersburg, MD, 2019.

[39] Anders Carlsson. *The back-to-back converter: control and design*. PhD thesis, Department of Industrial Electrical Engineering and Automation, Lund Institute of Technology, Lund, Sweden, 1998.

[40] Fattah Hassanzadeh, Hossein Sangrody, Amin Hajizadeh, and Shahrokh Akhlaghi. Back-to-back converter control of grid-connected wind turbine to mitigate voltage drop caused by faults. In *2017 North American Power Symposium (NAPS)*, pages 1–6. IEEE, 2017.

[41] Klaehn Burkes, Joe Cordaro, Tom Keister, and Kerry Cheung. Solid state power substation roadmap. *US Department of Energy, Washington, DC, Dec*, 2017.

[42] Yang Thee Quek, Wai Lok Woo, and Logenthiran Thillainathan. Iot load classification and anomaly warning in elv dc picogrids using hierarchical extended k -nearest neighbors. *IEEE Internet of Things Journal*, 7(2):863–873, 2020.

[43] LBNL. Integrated modeling tool for regulators - distribution grid locational performance modeling: Developing a foundational integrated modeling tool for regulators. https://www.districtenergy.org/HigherLogic/System/DownloadDocumentFile.ashx?DocumentFileKey=c7b57d8f-13ad-9bd7-1361-8a21a8a72a50&forceDialog=0, note=[Online; accessed 17-March-2021].

[44] J. Carvallo, J. Taneja, D. Callaway, and D. M. Kammen. Distributed resources shift paradigms on power system design, planning, and operation: An application of the gap model. *Proceedings of the IEEE*, 107(9):1906–1922, 2019.

[45] LBNL. Electric system planning. https://emp.lbl.gov/research/electric-system-planning, 2021.

[46] LBNL. Future of electric utility regulation. https://emp.lbl.gov/projects/feur/, 2021.

[47] Natalie Mims Frick, Snuller Price, Lisa C. Schwartz, Nichole L Hanus, and Ben Shapiro. Locational value of distributed energy resources. Technical report, Lawrence Berkeley National Laboratory, 2021.

[48] Michael Sullivan, Myles T Collins, Josh Schellenberg, and Peter H Larsen. Estimating power system interruption costs: A guidebook for electric utilities. Technical Report LBNL-2001164, Lawrence Berkeley National Laboratory, 7 2018.

[49] Roger C. Dugan and Thomas E. McDermott. An open source platform for collaborating on smart grid research. In *2011 IEEE Power and Energy Society General Meeting*, pages 1–7, 2011.

[50] DOE. Energyplus. https://energyplus.net/, 2021.

[51] Donald J. Hammerstrom and Hung Ngo. A transactive network template for decentralized coordination of electricity provision and value. In *2019 IEEE PES Transactive Energy Systems Conference (TESC)*, pages 1–5, 2019.

[52] L. Ljung and T. Glad. *Modeling of Dynamic Systems*. Prentice-Hall information and system sciences series. PTR Prentice Hall, 1994.

[53] F.E. Cellier and E. Kofman. *Continuous System Simulation*. Continuous System Simulation. Springer, 2006.

[54] Peng Wang, Bishnu Bhattarai, Jianming Lian, Donald J. Hammerstrom, and Ke Ma. A unified virtual battery model for responsive assets. In *2019 IEEE Power and Energy Society General Meeting (PESGM)*, pages 1–5, 2019.

[55] IEEE. Ieee recommended practice for interconnecting distributed resources with electric power systems distribution secondary networks. *IEEE Std 1547.6-2011*, pages 1–38, 2011.

[56] Miguel Heleno, David Sehloff, Antonio Coelho, and Alan Valenzuela. Probabilistic impact of electricity tariffs on distribution grids considering adoption of solar and storage technologies. *Applied Energy*, 279:115826, 12/2020 2020.

[57] Bryan Palmintier, Meghan Mooney, Kelsey Horowitz, Sherin Abraham, Tarek Elgindy, Kwami Sedzro, Ben Sigrin, Jane Lockshin, Brady Cowiestoll, and Paul Denholm. Chapter 7. distribution system analysis in the los angeles 100% renewable energy study. https://www.nrel.gov/docs/fy21osti/79444-7.pdf, 2021. [Online; accessed 16-August-2021].

[58] Kapil Duwadi, Killian McKenna, Akshay Jain, Kajal Gaur, Adarsh Nagarajan, and David Palchak. An analysis framework for distribution network der integration in india: Distributed solar in tamil nadu. https://www.nrel.gov/docs/fy21osti/78114.pdf, 2021. [Online; accessed 16-August-2021].

[59] Ronald B. Melton, Kevin P. Schneider, Eric Lightner, Thomas E. McDermott, Poorva Sharma, Yingchen Zhang, Fei Ding, Subramanian Vadari, Robin Podmore, Anamika Dubey, Richard W. Wies, and Eric G. Stephan. Leveraging standards to create an open platform for the development of advanced distribution applications. *IEEE Access*, 6:37361–37370, 2018.

[60] DOE. Volttron. https://volttron.org/, 2021.

[61] David Wenzhong Gao, Eduard Muljadi, Tian Tian, and Mackay Miller. Software comparison for renewable energy deployment in a distribution network. Technical Report NREL/TP-5D00-64228, National Renewable Energy Laboratory, 2 2017.

[62] JS Homer, Y Tang, JD Taft, AC Orrell, D Narang, M Coddington, M Ingram, and A Hoke. Electric Distribution System Planning with DERs – High-level Assessment of Tools and Methods. Technical Report PNNL-28138, Pacific Northwest National Laboratory, https://epe.pnnl.gov/pdfs/Electric_Distribution_System_Planning_Tools_PNNL-28138.pdf, March 2020.

[63] HELICS contributors. Tools integrated with HELICS. https://helics.org/tools/, 2021. [Online; accessed 22-March-2021].

[64] IEEE. Ieee standard for modeling and simulation (m s) high level architecture (hla)– framework and rules. *IEEE Std 1516-2010 (Revision of IEEE Std 1516-2000)*, pages 1–38, 2010.

[65] DOE. Spawn-of-energyplus. https://www.energy.gov/eere/buildings/downloads/spawn-energyplus-spawn, 2014.

[66] Andrey Bernstein and Emiliano Dall'Anese. Real-time feedback-based optimization of distribution grids: A unified approach. *IEEE Transactions on Control of Networked Systems*, 6(3):1197–1209, 2019.

[67] DOE. Behind-the-meter-storage (btms) overview. https://www.energy.gov/index.php/eere/vehicles/downloads/behind-meter-storage-btms-overview, 2020.

Appendix A – Existing Resource Descriptions

This appendix catalogs many of the software tools, data sets, and test beds relevant to DERs and distribution system research. The resources vary widely as to usability and quality, but assessment of those characteristics is not included. Before embarking on new development, a research team should review this catalog for possible starting points, test cases, gap analyses, collaborators, advisors, and co-simulation federates. The list is arranged alphabetically.

A.1 Simulation Tools

This section summarizes nearly 40 software tools that could be available for national laboratory research. Many, but not all, were developed by the national laboratories. The emphasis is on tools that are published or will be published under an open-source license, because they are more readily available to other researchers.

A.1.1 Advanced Distribution Management System (ADMS) Test Bed

The National Renewable Energy Laboratory (NREL) ADMS test bed is an evaluation and research platform. It comprises software simulations of large-scale distribution systems and field equipment integrated through power-, controller-, and remote- hardware-in-the-loop capabilities that realistically represent a power distribution system, allowing utilities to evaluate next-generation ADMS control. This test bed can simulate building end-use loads, home energy management system controllers, and distribution circuits using the Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS).

Web page: https://www.nrel.gov/grid/advanced-distribution-management.html

A.1.2 BEAM

The modeling framework for Behavior, Energy, Autonomy, and Mobility (BEAM) provides an agent-based simulation environment for the transportation infrastructure. BEAM was developed by researchers at Lawrence Berkeley National Laboratory (LBNL). While incorporating user behaviors and changing mobility needs, it can model complex urban traffic patterns. It is already in use at multiple laboratories to study the effects of EV charging on the electricity infrastructure.

Web page: https://beam.lbl.gov/

A.1.3 CIMHub

CIMHub is a module of GridAPPS-D that provides just the feeder model conversion tools. It is built around a Common Information Model (CIM) feeder model in a triplestore database. The supported inputs are CIM XML, OpenDSS, CYMDist, and Synergi Electric for distribution systems. Other input formats are in development for transmission systems.

The supported output formats are GridLAB-D, OpenDSS, and raw comma-separated value (CSV) for distribution systems. Other formats are in development for transmission systems and EMT models. Besides feeder model translation, Pacific Northwest National Laboratory (PNNL) uses CIMHub to develop and propose extensions to the CIM standard. CIMHub is open source under the Berkeley Software Distribution (BSD) license, and installable as a Docker container.

Web page: https://github.com/GRIDAPPSD/CIMHub

A.1.4 Cyber-Energy Emulation Platform (CEEP)

NREL’s CEEP enables researchers to safely explore the vulnerabilities of the inter-dependencies of power systems and network communication flows. CEEP can emulate distribution networks comprising commercial building load, EV chargers, and smart homes with solar power and diesel backup. It allows users to introduce cyberattack scenarios. CEEP provides a visualization platform for a detailed representation of entire distributed energy systems and analysis of the risks of cybersecurity threats.

Web page: https://www.nrel.gov/grid/cyber-energy-emulation-platform.html

A.1.5 Demand-Side Grid Model (dsgrid)

NREL’s dsgrid builds on decades of sector-specific energy modeling expertise to understand current and future U.S. electricity demand for power systems analyses. The model can create detailed electricity load data sets at high temporal, geographic, sectoral, and end-use resolution to enable comprehensive analyses of current patterns and future projections of end-use loads. NREL component models such as ResStock (single-family detached home models) and ComStock (commercial building models) are used in dsgrid.

Web page: https://www.nrel.gov/analysis/dsgrid.html

A.1.6 DER-CAM

The Distributed Energy Resources Customer Adoption Model (DER-CAM) is a decision support tool designed primarily for finding optimal distributed energy resource (DER) investments in the context of either buildings, or microgrids with multiple resource types. DER-CAM can be used to find the optimal portfolio, sizing, placement, and dispatch of a wide range of DERs, while co-optimizing multiple stacked value streams that include load shifting, peak shaving, power export agreements, or participation in ancillary service markets. DER-CAM is technically mature and extensively peer reviewed; researchers at Lawrence Berkeley National Laboratory have been developing DER-CAM since 2000.

While the objective function of DER-CAM can be easily modified—or even replaced by a multi-objective analysis—it is most commonly defined as the total annual cost of a site’s energy supply. This includes costs associated with both new and existing DERs, operation and maintenance costs, fuel costs, and also all costs related to utility imports, whether fixed, time dependent, energy based, or power based. Additionally, all value streams associated with the optimal DER dispatch determined by DER-CAM are considered in the objective function, in the forms of both avoided costs and market participation.

Web page: https://gridintegration.lbl.gov/der-cam

A.1.7 Distributed Generation Market Demand (dGen)

NREL’s dGen is a customer adoption model and can be used to analyze the key factors that will affect future market demand for DERs at multiple geographic levels (national, state, and utility, or below). NREL’s dGen uses a bottom-up, agent-based approach to model customer adoption.

Web page: https://www.nrel.gov/analysis/dgen/

A.1.8 Distribution Grid Integration Unit Cost Database

NREL has created a distribution grid integration unit cost database using data from a variety of utilities, photovoltaic (PV) developers, technology vendors, and published research reports. This database contains the unit cost information of various grid components, such as voltage control assets (e.g., line regulators, transformers), telemetry, supervisory control and data acquisition (SCADA), and DER storage, that may be required to integrate increasing amounts of distributed solar PV into distribution systems. The database is used for studies on DER integration and network planning and upgrades.

Web page: https://www.nrel.gov/solar/distribution-grid-integration-unit-cost-database.html#:~:text=NREL's%20Distribution%20Grid%20Integration%20Unit,(PV)%20onto%20distribution%20systems.&text=Analysts%3A%20Improving%20estimates%20of%20costs,system%20and%20identifying%20cost%20drivers

A.1.9 Distribution Integration Cost Options (DISCO)

DISCO provides a readily user-expanded set of analysis workflows (e.g., quasi-static time-series hosting capacity, upgrade analysis, DER effects, and postprocessing to summarize) that can be efficiently applied to arbitrarily large sets of feeders. DISCO can be used for the following: (1) DER impact analysis and advanced hosting capacity (e.g., full annual time series with appropriate metrics and advanced controls), (2) to automatically determine required distribution grid upgrades and calculate their cost. DISCO does all of this efficiently at large scale (hundreds to thousands of feeders in much less than an hour). DISCO is currently an NREL in-house tool but there is a plan to make it an open-source tool in the future. DISCO was recently applied to NREL's distribution system analysis for the Los Angeles 100% Renewable Energy Study [57].

Web page: https://www.nrel.gov/solar/distribution-grid-integration-unit-cost-database.html

A.1.10 Distribution System Simulator

NREL's distribution system simulator is a high-performance, three-phase, unbalanced power-flow implementation coded from the base up in Julia, funded by NREL's Laboratory Directed Research and Development (LDRD) program. It provides an alternative to OpenDSS and other simulators. This tool is currently an NREL in-house tool, but there is a plan to make it an open-source tool in the future.

A.1.11 Distribution Transformation Tool (DiTTo)

Utilities use diverse modeling tools to store and analyze their distribution networks (e.g., OpenDSS, Synergi, Cyme, GridLAB-D, etc.). NREL's Distribution Transformation Tool (DiTTo) provides an open-source framework to convert models among the formats of these tools for research and analysis. DiTTo can implement a many-to-one-to-many parsing framework, which makes it modular and robust. Readers and writers are then implemented to perform the translation from a given format to the core representation and then to another specified format.

Web page: https://nrel.github.io/ditto/

A.1.12 Emerging technologies Management and Risk evaluation on distribution Grids Evolution (EMeRGE)

EMeRGE's capabilities include development of feeder models from GIS data (.shp files), developing PV scenarios (number of customers, PV size, volt/var, location), time-series power-flow analysis, and PV interconnection request impact assessment. EMeRGE has metrics including power quality risk metrics for both network and assets, transformer loss of life, energy loss efficiency, overgeneration, and customer hours in different categories of violations for assessing the effects of DER integration with the grid. EMeRGE has been applied to distribution analysis of large-scale intergration of rooftop solar in Tamil Nadu in India [58].

Web page: https://github.com/NREL/EMeRGE

A.1.13 EnergyPlus

EnergyPlus is an open-source tool for whole-building energy modeling. Its strongest features include thermal modeling of buildings, HVAC equipment, building energy controls, heat transfer, ventilation, and fenestration. Unlike the single-zone house model in GridLAB-D, EnergyPlus represents multiple HVAC zones. EnergyPlus was designed for evaluating building energy performance and potential improvements. The Building Technologies Office (BTO) began sponsoring its development in 2001 to replace the predecessor tools called BLAST and DOE-2. LBNL and NREL are the main development organizations, with support from others. EnergyPlus can run from the command line or a relatively primitive user interface, so many users access the program through OpenStudio, a product of NREL, Argonne National Laboratory (ANL), LBNL, Oak Ridge National Laboratory (ORNL), and PNNL. Without OpenStudio, it is difficult for non-experts to build an EnergyPlus model.

The EnergyPlus code was converted from Fortran to C/C++, and is open source. It can be installed or built on Windows, Linux, or Mac OS X. There can be important differences between ”point releases” of EnergyPlus, which must be considered in upgrading building models to new versions. For single-family residences, the simplified house model in GridLAB-D is usually sufficient. For larger buildings that have multiple HVAC zones, there is no practical alternative to EnergyPlus. BTO has been sponsoring Modelica-based successors to EnergyPlus, but these currently require more expertise of the user and also a commercial Modelica solver.

For grid integration research, EnergyPlus has two main limitations after the basic model has been constructed and validated. First, the EnergyPlus loads do not respond to voltage and do not consider reactive power. The researcher must handle such effects another way. Second, EnergyPlus was designed for hourly time steps. Primarily because the assumptions made throughout EnergyPlus modules are quasi-static, instability may occur at a time step shorter than 5 minutes, i.e., specified as 12 steps per hour to EnergyPlus. GridLAB-D and OpenDSS time-series power-flow simulations typically run at time steps of 1 to 60 seconds, which is faster than EnergyPlus. As a result, the effects of switching loads from EnergyPlus may not be properly diversified in feeder-level simulations.

Web page: https://energyplus.net/

A.1.14 Electric Vehicle Infrastructure Projection Tool

NREL's Electric Vehicle Infrastructure Projection Tool (EVI-Pro) models the build-out of the electric vehicle infrastructure and driving patterns. EVI-Pro spatially captures driving patterns, location, and requirements for electric vehicle charging infrastructure. It also temporally captures energy use and demand throughout the day. EVI-Pro uses bottom-up models to identify the optimal network of charging stations to support travel demand.

Web page: https://www.nrel.gov/transportation/evi-pro.html

A.1.15 Gasmodels.jl

Gasmodels.jl is a steady-state optimization package for gas networks, implemented in the Julia programming language with a JuMP package for mathematical optimization. It has a HELICS interface and may be considered for co-simulation of the electricity and natural gas sectors. Los Alamos National Laboratory is the developer, and the open-source license is BSD.

Web page: https://lanl-ansi.github.io/GasModels.jl/latest/

A.1.16 GridAPPS-D

GridAPPS-D is a Grid Modernization Laboratory Consortium (GMLC) project funded by the U.S. Department of Energy (DOE) Office of Electricity (OE) to develop an open-source, standards-based platform for development of advanced distribution system applications [59]. The objective is to reduce the time and cost of adopting new applications, which may result from DOE-funded research projects or come from third-party vendors. Utilities have identified vendor lock-in as a key barrier to adoption of advanced applications; GridAPPS-D can accommodate applications from different sources. From the researcher's perspective, GridAPPS-D offers a test bed with access to small and large test circuits.

The development team includes PNNL, NREL, Washington State University, University of Alaska-Fairbanks, Incremental Systems, and Modern Grid Solutions along with a large Industry Advisory Board (IAB). GridAPPS-D incorporates other tool sets described in this appendix, including GridLAB-D, OpenDSS, and HELICS to date. The platform adds:

- advanced database management for the CIM in a triplestore and time-series database
- support modules for the graphical user interface (GUI), authorization, testing, logging, and others
- DNP3 and OpenFMB interfaces to external systems
- a common API for application developers to use platform data and services.

Several sample applications have been developed by different members of the project team, with more applications in in progress. Some areas of current research interest, such as DER optimization, are expected to produce multiple applications. This is part of the desired end state: promoting the evaluation of alternative applications and avoiding vendor lock-in. The following applications are currently available or in development:

- visualization, i.e., the GUI is an application that could be replaced with another
- volt-var optimization
- distribution system state estimation
- model validation

- transactive energy system (includes the VOLTTRON environment internally [60])
- reconfiguration and service restoration with DERs
- DER optimal dispatch (two varieties)
- forecasting (two varieties)

GridAPPS-D is installable as a Docker container, and it also runs in the cloud. The first application-developer training session has been delivered privately, and was based on Jupyter notebooks in Python. The platform has been used to develop extensions to the CIM for DERs, and to develop and test a new proposed IEEE test circuit for operations; see Figure 12.

Web page: https://gridapps-d.org/

A.1.17 GridLAB-D and OpenDSS

GridLAB-D and OpenDSS are open-source distribution-circuit simulators. Several of the national laboratories use one or both in research projects. Both have been open source under BSD license terms since 2008, both can be customized, and both have been widely used in the research community. Since 2008, both programs have pioneered time-series power flow for distribution circuits, which has proven essential for technical analysis of variable DERs. GridLAB-D and OpenDSS have many overlapping capabilities, as listed in Table A.1, but some unique features are summarized in the last row. Neither implements all smart inverter functions from IEEE Standard 1547; OpenDSS lacks frequency response while GridLAB-D lacks autonomous adjustment of reference voltage and dynamic voltage support. For additional comparisons between these tools and those used at utilities, see the NREL report [61] and a subsequent GMLC report [62].

These tools have been encapsulated in frameworks like Python interface for OpenDSS (PyDSS) at NREL, or GridAPPS-D and TESP at PNNL. Anecdotally, OpenDSS has been more flexible in representing the unusual wiring connections found in real utility systems. It solves power flow faster and modeling errors are easier to debug. However, it lacks key features that are currently found only in GridLAB-D. These include houses, end-use loads, weather, and microgrid dynamics.

GridLAB-D Web page: https://www.gridlabd.org/

OpenDSS Web page: https://smartgrid.epri.com/SimulationTool.aspx

A.1.18 HELICS

HELICS is a co-simulation framework that provides time synchronization and message brokering between multi-domain simulators. For example, a HELICS co-simulation may federate MATPOWER for the bulk power system and real-time market, GridLAB-D for the distribution system, and EnergyPlus for several large buildings. The user has to set up the messaging schema and supply a HELICS configuration file for each simulator federate. Several simulators have a native HELICS interface. Others can be federated if they have their own automation interface, by using a functional mockup interface [63]. One advantage of co-simulation is that each domain simulator can use an existing, validated, and possibly large model. Another advantage is that best-of-breed simulators can be used in each domain.

HELICS is a GMLC project with participation by ANL, Idaho National Laboratory, Lawrence Livermore National Laboratory, NREL, ORNL, PNNL, and Sandia National Laboratories (Sandia). Most of the national laboratories and many universities had already developed

Table A.1. Comparison of GridLAB-D and OpenDSS

Characteristic	**GridLAB-D**	**OpenDSS**
Downloads	>100,000	>100,000
Language	C/C++	Delphi/Free Pascal
Power Flow	Newton-Raphson	Fixed-Point
Equation Solvers	KLU	KLU METIS
Automation Methods	HELICS FNCS TCP/IP Server	Windows Component Object Model HELICS FNCS (Framework for Network Co-Simulation) TCP/IP Server Direct DLL (dynamic link library)
Variants	PNNL SLAC	EPRI v8 EPRI v7 (Free Pascal) University of Central Florida
Uniqueness	End-use loads House thermal envelopes HVAC thermostats Schedules by day and time Weather Markets Transients, aka Delta Mode Grid-forming inverters Machine dynamics	Fault current calculation Relays and fault interruption Harmonics Wiring by phase Positive sequence mode

co-simulation frameworks before the advent of HELICS; however, they were costly to develop and not compatible with each other. Incompatibility defeats the purpose of co-simulation, which highlights one of the most important advantages of HELICS for the national laboratories. It is much easier to collaborate with tools and models when all parties adhere to the same standard. HELICS is partially compliant with IEEE 1516 [64]. (We believe no software fully implements that multi-part standard). HELICS does not yet match the performance of earlier co-simulation frameworks, but it does offer more features. It was designed to scale up, and its performance keeps improving.

Web page: https://helics.org/

A.1.19 Integrated Modeling Tool (IMT)

IMT models the interactions between consumers' adoption of DERs, utility grid planning, and utility rate design. It comprises three main steps: (1) An adoption model that considers the cost/revenue provided by the utility tariffs; the model is used to simulate thousands of individual DER adoption events in the nodes of the distribution grid. (2) A distribution grid planning model that determines the utility investments needed to accommodate the behind-the-meter (BTM) DER deployment. (3) A rate design model that allocates the utility hosting costs back to the tariffs and produces a set of economically stable rates.

Web page: https://gridintegration.lbl.gov/integrated-modeling-tool-imt

A.1.20 Interruption Cost Estimate (ICE) Calculator

The ICE Calculator is a web-based tool that estimates the costs of electric service interruptions, and the value of reliability improvements. Planners at utilities, government organizations, and other stakeholders use ICE Calculator for case studies. LBNL and Nexant are the developers.

Web page: https://www.icecalculator.com/home

A.1.21 MATPOWER

MATPOWER is not a product of national laboratories, but it is readily available to them as an open-source tool for power flow, continuation power flow, optimal power flow (OPF), unit commitment (UC), and stochastic multi-interval UC/OPF analyses on the bulk power system. MATPOWER was funded by the Power System Engineering Research Center at Cornell University, and has accumulated over 250,000 downloads. Most of the national laboratory staff who earned graduate degrees in electric power systems have some experience with MATPOWER. Similar to the situation with OpenDSS, MATPOWER is a base capability for the national laboratories.

MATPOWER is provided as a set of MATLAB source files under the BSD license, to be installed on top of either MATLAB or the open-source GNU Octave. It is not the first choice for distribution system analysis, but MATPOWER should be considered for analyzing DER impacts on the bulk power system, including electricity markets. Because it is well documented and widely used, MATPOWER models are readily transferrable to other research teams.

Web page: https://matpower.org/

A.1.22 Microgrid Design Toolkit

MDT is a decision support tool for microgrid planning, incorporating Pareto front optimization of multiple objectives, including cost, performance, and reliability. DER is one of the design options considered. Sandia is the developer.

Web page: https://www.sandia.gov/CSR/tools/mdt.html

A.1.23 ns-3 and OMNeT++

A discrete-event communication network simulator is used in co-simulations of the electric power distribution system with a communication and control network. A typical use case might involve DER and meters, each having interactions with both the power and communication networks. The power network is analog and uses continuous time signals, while modern communication networks are typically digital and use discrete time signals. This leads to significant differences in the models and simulators for each domain. National laboratories typically use one of two options developed elsewhere.

ns-3 is a discrete-event communication network simulator for educational and research use, implemented in C/C++ and available under a GNU General Public License (GPL) open-source license. It has a HELICS interface, and many HELICS examples have been done using ns-3.

Web page: https://www.nsnam.org/

OMNet++ (Objective Modular Network Testbed in C++) is another discrete-event communication network simulator, implemented in C/C++ and available under an ”Academic Public License” that is described as being similar to GPL. There is a prototype HELICS interface, but there may not be as many HELICS examples as with ns-3.

Web page: https://omnetpp.org/

A.1.24 Object-oriented Controllable High-resolution Residential Energy Model (OCHRE)

NREL has developed a residential energy model for grid and home energy co-simulation, OCHRE. OCHRE is a controllable thermal-electric residential energy model that captures building thermal dynamics, integrates grid-dependent electrical behavior, contains models for common DERs and end-use loads, and simulates at a time resolution down to one minute. It includes models for space heaters, air conditioners, water heaters, EVs, photovoltaics, and batteries that are externally controllable and integrated in a co-simulation framework. The model captures the end-use load of key controllable appliances and models active power, reactive power, and voltage dependences. It integrates with controllers and distribution models in building-to-grid co-simulation platforms. OCHRE is currently an NREL in-house tool but there is a plan to make it an open-source in the future.

Article: https://www.sciencedirect.com/science/article/pii/S0306261921002464

A.1.25 OpenModelica

OpenModelica is an open-source implementation of the Modelica modeling language, compiler, and simulator. Considered a simulation environment, Modelica is not optimized for electric power systems, but it has wide applicability for mixed-domain systems, such as automobiles, aircraft, and buildings. BTO is developing a Modelica-based successor to EnergyPlus, called Spawn of EnergyPlus [65], along with a Modelica library for buildings. At least some of these components currently require a commercial Modelica product to run, i.e., OpenModelica cannot solve them. If that situation changes, OpenModelica would become a viable open-source option, even though it is not a national laboratory product. The open-source license options for OpenModelica include GPL, and two others for members of the Open Source Modelica Consortium. There was a second open-source implementation called JModelica, but that variant was commercialized in 2019.

Web page: https://www.openmodelica.org/

A.1.26 POLARIS Transportation Systems Simulation Tool

POLARIS is an agent-based transportation system simulator on the regional scale, originally funded by the U. S. Department of Transportation and continued by the Vehicle Technologies Office (VTO) under an open-source license. It links with a vehicle powertrain simulator called Autonomie, funded by VTO and free of charge to DOE-funded researchers. POLARIS is implemented in C++ and Autonomie runs with Matlab/Simulink. POLARIS has a HELICS interface and may be considered for co-simulation of the electricity and transportation sectors. ANL developed both.

Web page: https://vms.es.anl.gov/POLARIS/Index

Article: https://doi.org/10.1016/j.trc.2015.07.017

A.1.27 PREconfiguring and Controlling Inverter SEt-points (PRECISE)

NREL has developed PRECISE to enable utilities to quickly establish optimal inverter settings (e.g., volt-var, volt-watt) for distributed solar PV systems using quasi-static time-series

simulations and optimal power-flow models. PRECISE uses the customer's network location, along with bottom-up solar and distribution network models, to estimate optimal inverter settings that will provide necessary control performance and minimize PV energy curtailment. PRECISE is used in the interconnection process to assess the impacts of a given interconnection application, and proposes inverter settings that help grid integration and avoid the need for capacity upgrades (e.g., new distribution transformers).
Web page: https://www.nrel.gov/grid/precise-tool.html

A.1.28 PyDSS

NREL has developed an open-source python wrapper and interface for EPRI's OpenDSS to enhance its organizational, analytical, and visualization capabilities. As a high-level Python package, PyDSS simplifies co-simulation framework integration and allows users the flexibility to develop custom control algorithms and embed them into the simulation environment. PyDSS uses OpenDSSDirect.py, a cross-platform Python package, to provide a high-level Python interface for OpenDSS.
Web page: https://github.com/NREL/PyDSS

A.1.29 Real-Time Optimal Power Flow (RT-OPF/OptGrid)

RT-OPF/OptGrid solves real-time optimal power flow problems at the grid edge and can optimize power flow between devices, including aggregations of DER. Each DER (or aggregation) optimizes for the voltage and power exchange at its interface to the grid. A linear approximation to network power flow, or an OpenDSS power flow solution, is used to enforce Kirchhoff's Laws within the distribution network [66]. RT-OPF/OptGrid can be used to manage DERs to their full potential for the grid's efficiency and resilience.
Web page: https://www.nrel.gov/grid/optgrid-controls.html

A.1.30 ReEDS

The Regional Energy Deployment System (ReEDS) is a planning tool designed by NREL. It can simulate the bulk system expansion scenarios from the present day through 2050 or later. By reflecting the regional attributes of energy generation and consumption, the model offers a high spatial resolution. It informs the long-term investment decisions related to the integration of renewable energy technologies. In addition to renewable generation, ReEDS can model other generation resources such as nuclear and fossil fuel-based plants.
Web page: https://www.nrel.gov/analysis/reeds/

A.1.31 Renewable Energy Integration & Optimization (REopt)

The REopt model can be used to optimize the size and operating strategy of a variety of renewable energy and energy storage projects; examples include energy storage, microgrids and resilience, campus planning, and the energy and water nexus. The REopt is formulated as a mixed-integer linear program to obtain an optimally sized mix of renewable energy, conventional generation, and energy storage technologies.
Web page: https://reopt.nrel.gov/

A.1.32 Renewable Energy Potential Model (reV)

The reV model is a spatio-temporal modeling assessment tool that allows users to estimate renewable energy capacity, generation, and cost based on geo-spatial intersection with grid infrastructure and land-use characteristics. It includes highly dynamic, user-defined modules that function at different spatial and temporal resolutions, allowing users to assess resource potential, technical potential, and supply curves at varying levels of detail.

Web page: https://www.nrel.gov/gis/renewable-energy-potential.html

A.1.33 REPAIR

The Risk-controlled Expansion PlAnning with dIstributed Resources (REPAIR) model, developed by LBNL, provides the foundational capabilities to enable risk-controlled decisions in utility grid planning to prevent and mitigate the effects of outages caused by regular equipment failures and/or high impact low probability (HILP) events, such as storms, earthquakes, or wildfires that may cause longer-term interruptions of service from the transmission system.

REPAIR model adds resilience and reliability metrics to the current network expansion and integrated resources planning process and delivers risk-based optimal solutions for distribution grid investments, allowing informed and transparent “cost vs. risk” decisions regarding infrastructural planning of electric utilities. The model considers long-term resilience and reliability planning decisions that are directly related to infrastructure upgrade (e.g., line reinforcement, new substations, etc.) as well as to the deployment of microgrids and distributed energy resources.

Web page: https://gridintegration.lbl.gov/grid-planning-and-economics#:~:text=The%20Risk%2Dcontrolled%20Expansion%20Planning,Probability%20(HILP)%20events%2C%20such

A.1.34 ResStock and ComStock

ResStock and ComStock model the residential and commercial building stock respectively across the United States. The models are developed by NREL for the U.S Department of Energy. They use a diverse set of public and private data sets and offer a high spatial, temporal, and sectoral resolution. These tools can be applied by cities, states, manufacturers, and utilities to develop their business strategies and energy efficiency programs. Some key insights provided by the tools include energy savings through building improvements, the contribution of buildings toward emission targets, load flexibility potential of buildings, and energy efficiency measures for relieving grid congestion.

ResStock Web page: https://www.nrel.gov/buildings/resstock.html

ComStock Web page: https://www.nrel.gov/buildings/comstock.html

A.1.35 System Advisor Model (SAM)

NREL’s SAM is an open-source techno-economic software model that facilitates decision-making for various stakeholders in the renewable energy industry. SAM can model different types of DERs at different scales such as solar PV, battery storage (front-of-meter or BTM applications), concentrating solar power systems, wind power, fuel cells, biomass, and tidal energy systems. SAM’s financial models cover power purchase agreement, third-party ownership, and residential and commercial projects.

Web page: https://sam.nrel.gov/

A.1.36 Transactive Energy Simulation Platform

The Transactive Energy Simulation Platform (TESP) is an open-source, installable PNNL software package funded by OE. The purpose is to allow researchers in transactive energy systems to focus on developing new software agents. The public example agents include thermostat-controlled loads, double-auction markets, consensus mechanism between large buildings, and load shedding. Private example agents include optimal battery bidding and transactive power rationing. TESP incorporates HELICS, GridLAB-D, OpenDSS, EnergyPlus, PYPOWER, and ns-3 with supporting software to configure simulations and post-process results. Examples of linkage to MATPOWER/MOST, and Agent-based Modeling of Electricity Systems/Power System Simulation Toolbox (AMES/PSST, from Iowa State University), are also provided.

TESP Web page: https://tesp.readthedocs.io/en/latest/
AMES/PSST Web page: https://github.com/ames-market

A.1.37 Transportation Energy & Mobility Pathway Options

The Transportation Energy & Mobility Pathway Options^{TM} (TEMPO) model at NREL captures technology adoption, travel mode choices, infrastructure evolution and energy demand of future transportation pathways. TEMPO uses bottom-up technology models and can be combined with macro-economic integration assessment models to analyze transportation pathways. TEMPO is being used to inform power system models and explore the interactions with transportation under increasing levels of transportation electrification.

Web page: https://www.nrel.gov/transportation/tempo-model.html

A.1.38 Xyce

Xyce^{TM} is a circuit simulator with features comparable to those of Simulation Program with Integrated Circuit Emphasis (SPICE) (the name Xyce was chosen to rhyme with SPICE). Xyce was developed by Sandia and released as open source with a GPL license. It has some single-phase electric power system components. Xyce has been designed to take full advantage of parallel computing where available, from desktop systems on up in size. Therefore, it may provide a good starting point for large-scale transient and harmonic solvers on power distribution systems.

Web page: https://xyce.sandia.gov/

A.2 Data Sets

A.2.1 ARPA-E Data Sets from National Laboratories

ARPA-E has funded several projects from the GRID DATA call that have produced models of interest for DER evaluation. These data sets contain realistic (not real) models that are used by the researchers without requiring special access permissions from the utilities. The projects led and hosted by National Laboratories include:

- DR POWER, performed by PNNL and National Rural Electric Cooperative Association (NRECA).

- SMARTDATA, performed by NREL, Massachusetts Institute of Technology and Illinois Institute of Technology.

Web page (DR POWER): https://egriddata.org/
Web page (SMARTDATA):
https://arpa-e.energy.gov/technologies/projects/smartdata-grid-models

A.2.2 CIGRE Data Sets

Other notable data sets include test cases hosted by the International Council on Large Electric Systems (CIGRE), which is a global community of power system researchers and industry professionals. Some of these data sets are created by modifying IEEE test cases and are suitable for EMT studies. Others such as the active distribution network (ADN) model are more suitable for smart grid control and protection studies.
Web page:
https://e-cigre.org/publication/736-power-system-test-cases-for-emt-type-simulation-studies

A.2.3 IEEE Test Cases

There are several IEEE test cases hosted on repositories by the University of Washington, IEEE Power and Energy Society (PES), and MATPOWER. These test cases cover both transmission and distribution systems and can be used for power-flow and dynamic stability studies. The test cases cover a wide range of system sizes and possess variable typologies. For example, the 8500-node test feeder is commonly used to evaluate the scalability of power flow algorithms. An improvement over this model is the newly proposed 9500-node test feeder, shown in Figure 12 (right). Similarly, the 342-node low-voltage network test system can be used to evaluate the effectiveness of computational methods in urban distribution systems, illustrated in Figure 11.
Web page (transmission): https://labs.ece.uw.edu/pstca/
Web page (distribution): https://site.ieee.org/pes-testfeeders/resources/

A.2.4 OEDI Repository

The U.S. DOE hosts a centralized repository under the Open Energy Data Initiative (OEDI) project. The repository contains high-quality data sets originating in research performed or sponsored by DOE’s programs, offices, and national laboratories. The project aims to increase accessibility and collaboration by providing secure, universal access to DOE-funded research. The repository contains many different types of files, such as raw data files, reports, media, and reference documents.
Web page: https://data.openei.org/

A.2.5 Synthetic Models for Advanced, Realistic Testing: Distribution Systems and Scenarios (SMART-DS)

Real distribution network electrical data sets are typically limited in accessibility and not readily shared by utilities. These data are needed in developing, enhancing, and validating advanced algorithms and the assessment of emerging DERs. NREL has created near-replicas of electricity grid data sets, realistic down to individual customer points of connection, and up to their connection with bulk system transmission. SMART-DS provides high-quality, synthetic distribution network models for DER analysis. With SMART-DS, users can test, improve, and assess electric power distribution systems research, (such as advanced distribution management system capabilities and DER integration analysis), on synthetic realistic networks. SMART-DS allows for scenario analysis of penetrations of multiple types of DERs, has a detailed statistical summary of the U.S. distribution systems, and can represent very large systems up to 100+ substations, 500+ feeders, 1 million+ customers.

Web page: https://www.nrel.gov/grid/smart-ds.html

A.2.6 Texas A&M University Synthetic Grids

Texas A&M University hosts a repository containing electricity grid test cases and data sets. Some of them include test cases ACTIVSg2000, ACTIVSg25k, and ACTIVSg70k that mimic the electricity grid in the Electric Reliability Council of Texas footprint and the western and eastern United States, respectively. The repository also hosts a combined model that can run synthetic power flow cases on the footprint of the continental United States. Moreover, a combined transmission and distribution synthetic data set is also provided that consists of 307,236 end-use customers and covers voltages from 120 V to 230 kV. Like other synthetic data sets, these models do not resemble the actual grid except that the generation and load profiles are similar to the actual ones.

Web page: https://electricgrids.engr.tamu.edu/

A.3 Test Beds

A.3.1 Electricity Infrastructure Operations Center (EIOC)

The EIOC at PNNL includes two independent utility control room environments tied together with a dedicated network and server enclave. These control rooms operate independently from PNNL’s campus network, and feature their own externally facing, firewalled, high-bandwidth fiber internet connection. The EIOC provides access to live data feeds from synchrophasors and other data sources.

Web page: https://www.pnnl.gov/projects/eioc

A.3.2 Energy Systems Integration Facility (ESIF) and Advanced Research on Integrated Energy Systems (ARIES)

NREL’s ARIES provides a research platform with experimentation capability for microgrid and DER research up to 20 MW and virtual emulation environment powered by NREL’s 8-petaflop supercomputer. ARIES can allow research at the 20-MW level with various DER technologies such as EVs, renewable generation, hydrogen, energy storage, and GEB. ARIES can represent DER integration at multiple scales and across different critical infrastructures to provide a detailed understanding of the effects of energy systems integration. ARIES research thrust spans over five areas including coupling at-scale storage technologies—such as batteries + thermal, or batteries + hydrogen, power electronics, future energy infrastructure (transmission and delivery networks for a variety of advanced fuel types and infrastructures), and cybersecurity.

NREL’s ESIF provides integrated research capabilities for energy systems analysis that includes high performance computing, thermal integration infrastructure, hydrogen systems, energy data, cyber and control networks and a research electrical distribution bus (REDB) linking laboratories at ESIF. ESIF can be used for microgrid and DER research up to the MW-level. ARIES leverages ESIF capabilities and the two are connected through a virtual emulation environment.

ARIES Web page: https://www.nrel.gov/aries/

ESIF Web page: https://www.nrel.gov/esif/

A.3.3 Laboratory Homes

The PNNL campus hosts two identical, 1500 square foot homes, one designated the Baseline Home and the other the Experimental Home. These are used for side-by-side comparisons of new energy efficiency measures and BTM controls, including responsive loads.

Web page: https://labhomes.pnnl.gov/

A.3.4 powerNET

The powerNET test bed at PNNL is a remotely configurable, multi-user resource that provides an experimentation sandbox for power system research. The test bed is designed to enable a wide range of types and scales of experiments, by combining virtual, simulated, and physical equipment. powerNET builds upon the OpenStack Infrastructure as a Service cloud software with the additions of power system and virtual equipment. Secure, worldwide, remote access is available. Additionally, multiple simultaneous experiments can be run concurrently.

Web page:
https://www.pnnl.gov/projects/center-collaborative-cyber-physical-research/powernet-testbed

Appendix B – Project Planning Survey

In planning, the U.S. Department of Energy's (DOE's) Strategic Analysis/Strategic Priorities and Impact Analysis Team (SPIA/SA) identified the following research gaps in a survey of other Energy Efficiency and Renewable Energy (EERE) offices:

1. Analysis of integrated technology portfolios to assess combined effects and value rather than a series of single technology evaluations. Related questions and gaps include
    a. integrated energy planning that holistically considers multiple DER types and not just one technology
    b. effects of multiple types of DERs on load shape, rather than one DER type at a time
    c. interaction between rate design and operation of multiple DER types
    d. value of integrated DERs to provide grid services and ameliorate negative effects of individual technologies, including bulk power sector issues like variable renewable energy curtailment
    e. calibrated and validated distribution/feeder models representative of existing systems and for use in analysis of DER technologies, consistent across EERE analyses.

2. Integration of bulk-scale and customer high-resolution models. Large-scale models, such as Regional Energy Deployment System (ReEDS) and other capacity expansion models, lack coordination between demand-side, DER, and bulk generation options.

3. Cybersecurity activities need coordination across industries and within DOE. Original equipment manufacturers (vehicles, EV supply equipment, DERs), and grid operators have done work here, but there are gaps in interfaces between devices and the distribution system. Better understanding of EERE overlap with work by the Office of Cybersecurity, Energy Security, and Emergency Response would be helpful.

4. Understanding of what other DOE offices have funded in this area would help with developing new funding opportunity announcements and building on existing capabilities. Examples include medium-voltage direct distribution connections for EV charging within the Vehicle Technologies Office (VTO) and flexible manufacturing facilities within the Advanced Manufacturing Office. Ability to coordinate across DOE and EERE should be developed.

5. More information is needed about what tools decision makers would find helpful. With the information, new tools can be developed or existing tools can be adapted that help decision makers rather than being used only in the laboratory. For example, HELICS tools may be used by utilities and public utility commissions, but for now, HELICS is a laboratory tool used for laboratory analyses. The National Association of Regulatory Utility Commissioners and the National Association of State Energy Officials Task Force on Comprehensive Energy Planning is helping to determine what underlying analyses (forecasting, resource) are needed to support these planning methods.

6. We need to make sure information on completed projects feeds into related studies. We need processes to make sure we all have access to the same materials, analyses, and starting points. For example, how should we integrate results from the Behind-the-Meter Storage project [67] into other studies? (Office of Electricity [OE], SPIA/SA, Solar Energy Technologies Office [SETO], VTO, BTO)

7. New fundamental grid architectures are needed for high penetrations of DERs and for other objectives and technologies such as resilience, microgrids, and modularity. Understanding and envisioning complete frameworks (system, communications, sensing, and coordinating) are needed rather than just individual technologies. (OE)

8. Broader issues regarding valuation of DERs should be coordinated. We need ways to valuate DERs and fundamental grid components from different perspectives. Many DOE/laboratory and external organizations are working in this area. Information is needed on the current state of the art, DOE/laboratory status, and external (i.e., utility, industry, consumer) needs. Do we need more advanced capabilities? Do we need more tools that stakeholders can quickly put to use? (OE, SPIA/SA, SETO)

These inputs formed the initial set of requirements for Section 1 of the report.

Pacific Northwest
National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354
1-888-375-PNNL (7675)

www.pnnl.gov