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Microgrids as a Building Block for Future Grids – Topic 4

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Section 1

Executive Summary

This white paper is the fourth in a series of seven white papers in support of the DOE Microgrid R&D Program and presents a broad vision for future grids where microgrids serve as a building block along with technologies that would need to be developed, use case scenarios and the research targets.

The DOE Microgrid R&D Program vision is to facilitate the nation's transition to (1) a more resilient and reliable, (2) more decarbonized electricity infrastructure, in which (3) microgrids have a reduced cost and implementation times, while ensuring that microgrids support an equitable energy transition through prioritized provision of at least 40% of microgrid benefits going to disadvantaged communities in a secure manner. These three enumerated strategic goals are developed in the context that the United States' electricity system is becoming more distributed in nature, and that disruptions to the electricity delivery system (EDS) are occurring more frequently and with greater severity. The vision statement follows.

> *By 2035, microgrids are envisioned to be essential building blocks of the future electricity delivery system to support resilience, decarbonization, and affordability. Microgrids will be increasingly important for integration and aggregation of high penetration distributed energy resources. Microgrids will accelerate the transformation toward a more distributed and flexible architecture in a socially equitable and secure manner.*

The vision assumes a significant increase of DER penetration during the next decade, reaching 30-50% of the total generation capacity. In that context, the Microgrid R&D program seeks to accomplish these three goals:

> Goal 1: Promote microgrids as a core solution for increasing the **resilience and reliability** of the EDS, supporting critical infrastructure and reducing social burdens during blue and black sky events
>
> Goal 2: Ensure that microgrids serve as a driver of **decarbonization** for the US EDS by acting as a point of aggregation for larger number of DERs, with 50% of new installed DER capacity within microgrids coming from carbon-free energy sources by 2030.
>
> Goal 3: **Decrease microgrid capital costs** by 15% by 2031, while reducing **project development, construction and commissioning** times by 20%.

These goals additionally have cross-cutting topics of focus on equity and security in both R&D and partnered demonstrations. In regulatory R&D and demonstrations, focus will be on supporting an **equitable energy transition** through prioritized provision of at least 40% of microgrid benefits going to disadvantaged communities. In security, consideration for physical and cybersecurity research, and leveraging or teaming with appropriate entities advancing security through R&D will be considered.

This white paper is one of seven being prepared for the Department of Energy (DOE) Microgrid Research and Development (R&D) program as part of the strategy development for the next 10 years. The seven white papers focus on the following areas:

1. Program vision, objectives, and R&D targets in 5 and 10 years

2. T&D co-simulation of microgrid impacts and benefits
3. Building blocks for microgrids
4. **Microgrids as a building block for the future grid**
5. Advanced microgrid control and protection
6. Integrated models and tools for microgrid planning, designs, and operations
7. Enabling regulatory and business models for broad microgrid deployment

To achieve the three primary goals, the Microgrid R&D Program works in three categories:

Category 1: Technology development,

Category 2: Analysis and tools for planning, and

Category 3: Institutional framework.

This white paper, *Microgrids as a building block for the future grid*, is focused on Topic 4 and falls under *Category 1*. It presents concepts for how microgrids can become building blocks of the future grid and the value it could bring for electricity grid operation. In tune with this vision, architecture building upon a hierarchical framework is highlighted, where microgrids serve as a building block of the larger grid. It will take advantage of DERs and control technologies available within microgrids to improve system resilience during normal and emergency operating conditions, enhance operational flexibility and contribute to de-carbonization in a scalable manner.

Section 2

Introduction

Microgrids have long been viewed as a critical resource for supplying facilities with resilient power during emergencies and outages. In many well publicized power outages, the remediation plans have included the use of microgrids[1,2] and coordinated distributed resources—both renewable and traditional. However, the view of a microgrid as a fixed boundary, statically controlled and one-off solution has been evolving, through the ideas of embedded microgrids, networked microgrids and hierarchical frameworks that use microgrids as a building block, to microgrids enabling system-of-systems solutions for future grids.

This paper presents a broad vision for future grids where microgrids serve as a building block. While the exact evolution of the present grid to the future grid is unknown, it is largely envisioned that the future grid will see continued integration of distributed energy resources (DERs) and that grid architecture will need to evolve such that it is able to achieve effective monitoring and control of large numbers of DERs. It is anticipated that the future power system may see a rise in the installed capacity of DERs, to as much as 30%-50% of the total generation capacity [3]. At these penetration levels, the individual DERs must work together so that they can provide services to the various levels of the grid—distribution or transmission—in a systematic way, and maintain or improve reliability, power quality, affordability, operability, safety, while reducing carbon emissions. Microgrids provide a mechanism to be a point of aggregation for DERs. Through the leadership of the Department of Energy (DOE) and partnership with industry and academia, various microgrids have been deployed to date. As more and more microgrid installations and operations become a reality, the future may see more instances of networks of microgrids and hierarchical microgrids that offer flexibility, sustainability and a path to decarbonization. A mix of individual, segregated and networked microgrids could co-exist during the short-term future, while a more structured grid architecture with organized hierarchical or fractal microgrids could develop over the long-term. In other words, various specific architectural implementations are realizable; and while there could be multiple pathways to achieve a system of systems, they will likely see consistent needs in terms of technology development, and the common factor will be microgrids.

In summary, this paper envisions different possibilities for how microgrids can become building blocks of the future grid. In tune with this vision, one particular architecture building upon a hierarchical framework is specifically highlighted, where microgrids serve as a building block of the larger grid. It will take advantage of DERs and control technologies available within microgrids to improve system resilience during normal and emergency operating conditions, enhance operational flexibility and contribute to de-carbonization in a scalable manner.

[1] https://www.npr.org/2020/01/11/795248921/california-reservations-solar-microgrid-provides-power-during-utility-shutoffs

[2] NRECA (2021) The Value of Battery Energy Storage for Electric Cooperatives. January 2021, Business & Technology Report

[3] DOE OE 2021 Strategy White Papers on Microgrids: Program vision, objectives, and R&D targets in 5 and 10 years – Topic #1

Section 3

Vision for the Future

As discussed in the Topic 1 white paper, the future power system may see a ten-fold increase in distributed energy adoption, with 30%-50% of the generation assets connected at the distribution level. As more and more DERs are integrated into the grid, the number of active control points could likely become unmanageably numerous for current control approaches to effectively handle. Consider, for example, the distribution system of the San Francisco Bay Area with more than four million customers. Assuming each customer has at least one DER installed, this potentially leads to millions of control points. Today's existing control systems only work well when there are a limited number of active control points in the system, in the range of thousands of central power plants. In order to deal with these massive amounts of new DER technologies and the associated grid measurements they can provide, the current view of power grid planning and operations will need to be adapted to a framework that is amenable to large-scale DER penetrations. The framework will need to monitor, control, and optimize large-scale grids with significantly high penetration levels of variable generation and DERs; it will need to process the deluge of data from pervasive metering; and it will need to implement a variety of new market mechanisms, including multilevel ancillary services. At such high DER penetration levels, DERs connected at the distribution grid must support bulk system operations by providing bulk grid services to ensure system stability. Therefore, a future grid framework should be able to address large-scale aggregation of DERs for the provision of grid services.

Today's power grid largely uses a centralized control architecture. The increasingly large number of distributed assets cannot readily be integrated into existing centralized operational system architectures due to limitations in the scalability of control and computations. A number of other control frameworks have been proposed and discussed during the past few years, including decentralized, meshed, distributed and hierarchical control architectures. Figure 1 illustrates some of these control architectures. While each architecture has its own advantages and disadvantages, there is general consensus[4] that a more distributed framework[5] with hierarchical control and communication structure would provide greater benefits toward scalability of monitoring, control and communications, and the underlying computations for grid operation. A more hierarchical and distributed control approach is also advocated in the grid architectures developed under the DOE's Grid Modernization Laboratory Consortium[6].

[4] A. Bidram and A. Davoudi, "Hierarchical structure of microgrids control system," IEEE Transactions on Smart Grid, vol. 3, no. 4, pp. 1963–1976, 2012

B. D. Kroposki, "Basic research needs for autonomous energy grids: Summary report of the workshop on autonomous energy grids," National Renewable Energy Laboratory (NREL), Golden, CO (United States), Tech. Rep., September 2017

D. Molzahn, F. Dorfler, H. Sandberg, S. H. Low, S. Chakrabarti, R. Baldick, and J. Lavaei, "A survey of distributed optimization and control algorithms for electric power systems," IEEE Transactions on Smart Grid, February 2017

A. Bernstein and E. Dall'Anese, "Real-time feedback-based optimization of distribution grids: A unified approach," IEEE Transactions on Control of Network Systems, 2019

[5] https://gmlc.doe.gov/projects/1.2.1

[6] https://gridarchitecture.pnnl.gov/library.aspx, https://gmlc.doe.gov/projects/1.4.10

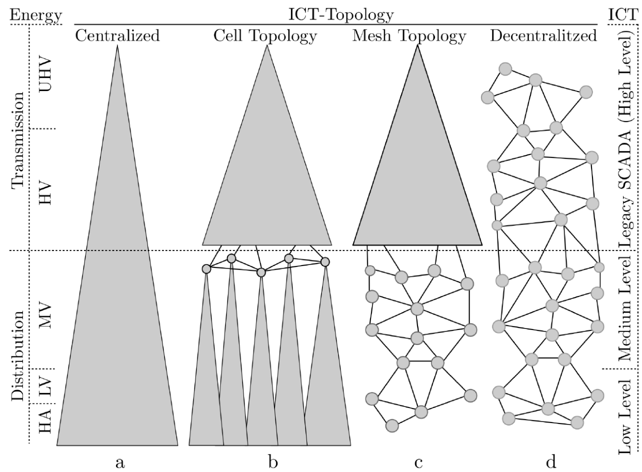

Figure 1 – Various architectural frameworks[7]

A hierarchical architecture option that offers a good way to effectively integrate the increasing number of distributed assets is shown in Figure 2. At the lowest level are individual renewable and conventional generation sources and loads, as well as storage such as electric vehicles and stationary batteries that have local controllers. Industrial, commercial and residential buildings are comprised of a combination of loads, generation and storage, and may have a building management system (BMS) or home energy management system (HEMS) that form the next level of control. Generation sources, storage and buildings co-located in a section of a distribution feeder are collectively managed by the next level of control, forming a "cell." These cells are not identical, but rather are unique combinations of local generation, storage and loads. Several co-located cells are then collectively managed by the next level of control, forming a cell at the substation level, and so forth. The Y axis shows the order of magnitude of control points at different levels in the hierarchy. This presents a coherent framework for managing millions of DERs and controllable loads in a scalable way, with decentralized or distributed control, and optimization as core tools to enable scalability.

Through this hierarchical control, each cell participates in optimal operation of the grid under normal grid conditions. For operations under emergency grid conditions, we can also consider a future with increased presence of DERs that can set voltage and frequency for loads when grid power is lost—including modular fossil and natural gas assets such as diesel generators and inverter-connected renewable sources and stationary battery or flywheel energy storage systems with grid-forming inverters[8]—deployed by consumers or utilities, to provide increased resilience for individual sites (e.g., a building or campus) during extreme events. To increase reliability and resilience of the overall power system, these sources, when aggregated along with more traditional DERs and loads, would allow cells to form microgrids. The degree to which distributed assets are aggregated into microgrids depends on access to technical capabilities and available resources. A microgrid, according to the DOE definition, includes the ability to island[9]. This requires sufficient generation resources to supply all (or at least *all critical*) load within the boundaries of the microgrid and at least one source that can act as the microgrid's voltage and frequency master, as well as one or more switches that would allow the microgrid to island, so not all of the proposed hierarchical cells can operate as microgrids during resilience events. Power systems with higher penetration of DER that can set voltage and frequency will allow for a higher percentage of cells to transition to microgrids.

[7] P. Eder-Neuhauser, T. Zseby and J. Fabini, "Resilience and Security: A Qualitative Survey of Urban Smart Grid Architectures," in IEEE Access, vol. 4, pp. 839-848, 2016, doi: 10.1109/ACCESS.2016.2531279.

[8] https://www.nrel.gov/news/program/2020/technical-roadmap-guides-research-direction-grid-forming-inverters.html

[9] Dan Ton, Merrill Smith, "The US DOE's Microgrid Initiative," http://dx.doi.org/10.1016/j.tej.2012.09.013

During major disruptions, the hierarchical cell structure provides a starting point for *adaptive* microgrid formation, or large-scale *self-assembly*. In this way, microgrids become a fundamental building block of system planning and operations, increasing reliability and resilience.

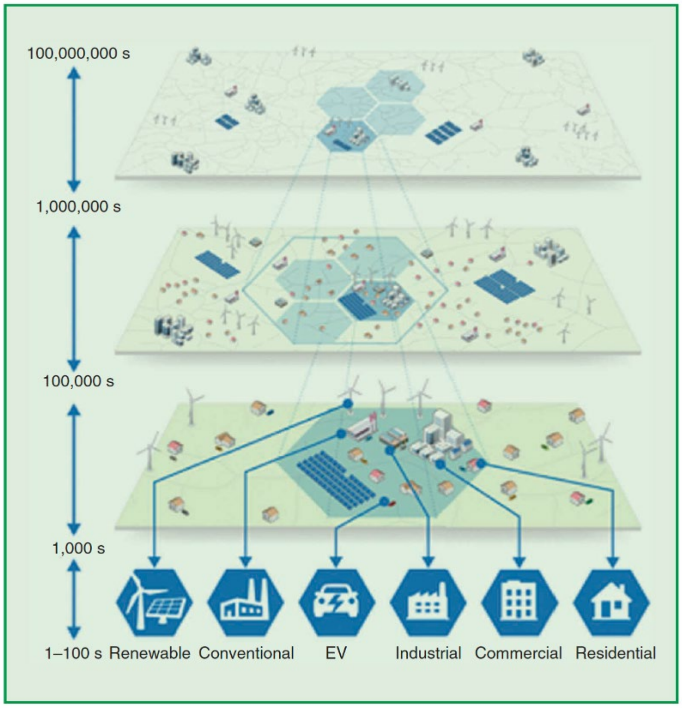

Figure 2 – A future grid vision with a hierarchical cell structure and distributed hierarchical control system that integrates individual technologies hierarchically into the bulk power system as the control points increase in number (NREL)

To illustrate this further, consider a hypothetical feeder shown in Figure 3. For the sake of simplicity, loads are not shown. This shows some cells that do not have adequate DERs to form a microgrid, indicated by green hexagons, as well as cells that can form microgrids, shown as blue hexagons. Sectionalizing switches required to allow microgrids to island are shown as black dots. In this example, we also illustrate the potential for individual microgrids to network in the top right, where two microgrids (blue hexagons) are shown within a larger microgrid, and that only portions of a cell may be able to operate as a microgrid, in the center, top and bottom, where a microgrid (blue hexagon) is shown within a cell (green hexagon). As more DERs are deployed across the feeder, the microgrid boundaries may expand, moving towards realization of the future vision of a grid with microgrids as building blocks.

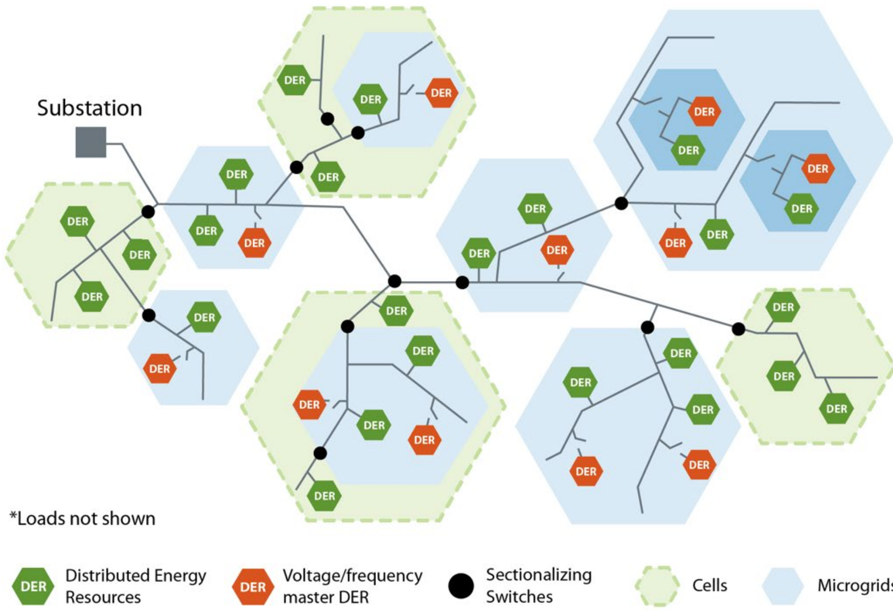

Figure 3 – Hypothetical distribution feeder with co-located cells shown as hexagons. Cells shown in blue are microgrids. Required sectionalizing switches are shown as black dots.

While a hierarchical framework effectively enables the vision of microgrids as a building block for future grids, one cannot ignore other pathways to the future as numerous DERs continue to be integrated into distribution systems and the present grid evolves into the future grid. The DERs will provide services to the local distribution system, as well as to the bulk system, individually or in an aggregated form. Microgrids provide a mechanism to bring the local DERs together to provide solutions for resilience and reliability by becoming their natural aggregation point. Microgrids form a unit that hosts loads and generation, that can be connected or disconnected from rest of the grid. Many microgrids have formed in the continental US and they co-exist with the rest of the network. In one future direction, microgrids will continue to form and will be linked with each other to form networked microgrids to work in a coordinated fashion[10]. Alternatively, neighboring microgrids having different customers may have a dynamic overlay if they dynamically change boundaries by network reconfiguration through switching operations, or merge into each other to form larger multi-customer, multi-property microgrids. The various future directions are not mutually exclusive; for example, aspects of networked microgrids may be combined with dynamic boundaries of microgrids. Various such architectures may form; however, they will likely have one common factor, which is microgrids. The different futures could converge to the proposed hierarchical framework, or in its strongest form, this system-of-systems may render a fractal grid. This is shown in Figure 4. The ultimate vision of a hierarchical structure would have many benefits such as ease of control, scalability of computations and data exchange.

[10] K.P. Schneider, H. Nagarajan, A. Pratt, et al., "Preliminary Design Process for Networked Microgrids," Technical Report PNNL-30066, June 2020.

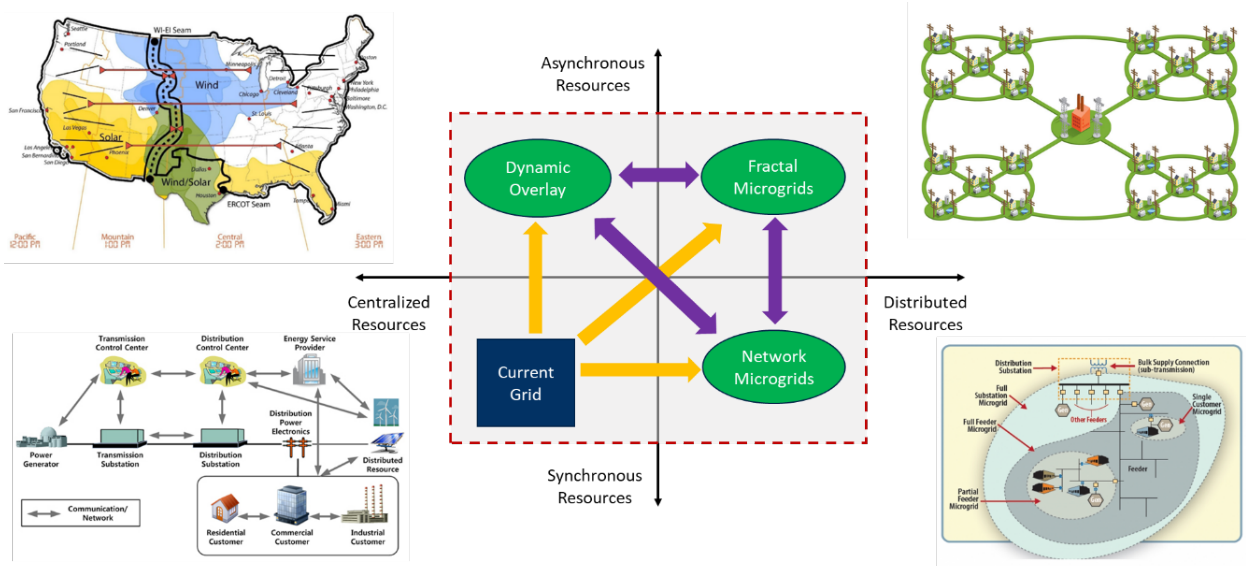

Figure 4 – Potential grid futures[11]

[11] US DOE, "Smart Grid System Report," 2020 Report to Congress

Section 4

Technology Developments

The proposed vision of a future grid leverages microgrids as a fundamental building block for robust and seamless system operations, and increased grid resilience during disasters, faults and manmade attacks. The realization of the future grid toward this vision will require several technologies. These include:

Control and Protection

- Distributed control and optimization capabilities for optimal operation of individual microgrids, networked microgrids, and a heterogeneous collection of microgrids, DERs and loads.
- Controls that make use of the latest advances in data analytics, machine learning, and artificial intelligence. Controls that monitor and maintain power quality.
- For cells to operate as microgrids, cell-level controllers that meet the requirements set out for microgrid controllers in IEEE 2030.7, including managing islanding and reconnection transitions, dispatch and steady-state voltage and frequency regulation, will be required.
- Advances in inverter controls, especially for grid-forming inverters[12], to address stability oscillation issues in low-inertia systems.
- The ability to distinguish, prioritize and selectively serve critical loads.
- Advances in protection coordination for networks with microgrids that can be operating in various combinations of grid-connected and islanded modes.

Analytics and algorithms

- Monitoring and state estimation tools based on advanced data analytics and machine learning.
- Optimization approaches that enable increased involvement of customers in demand side management through dispatching building loads and DERs in a coordinated way.
- Planning tools for optimal placement of devices and DERs to aid network reconfiguration and formation of microgrids.
- Distribution network reconfiguration algorithms to adapt to the propagation of faults and outages and that can dynamically form microgrids.
- Upgrades to utility management systems, such as advanced distribution management systems (ADMS), including the ability to host distributed, hierarchical controls.

Communications and Sensors

- Distributed communications capabilities between DERs and microgrids.
- Advances in sensor technologies for microgrid control and operation, with data privacy preservation. Continued advances in data interoperability and cybersecurity as elaborated in the White paper Topic 5 Advanced Microgrid Control and Protection.

Hardware

- Substation switch upgrades to accommodate feeder-level cells combining into a substation-level cell. Grid forming inverters hardware to support blackstart services.
- Leverage advanced hardware, such as solid-state transformers, supercapacitor and flywheel storage, in realistic hardware-in-the-loop simulations to help technology transition to field pilots.

[12] Y. Lin, J.H. Eto, B.B. Johnson, J.D. Flicker, R.H. Lasseter, et al, "Research Roadmap on Grid-Forming Inverters," https://www.nrel.gov/docs/fy21osti/73476.pdf

Section 5

Enabling Technologies

Design and implementation of a future grid architecture that uses microgrids as a building block would require close coordination with the other six topic area white papers. For example, Topic 2 co-simulation will enable an effective modeling and simulation framework to demonstrate the envisioned architecture for planning and operational scenarios. Topic 5 will provide the appropriate control and protection technologies for various microgrids to work together in a networked or hierarchical manner, or in different combinations in between. Topic 6 will make available the correct tools for planning, design and operations of future grids. Topic 7 will provide the appropriate regulatory and business models for broad microgrid deployment.

The proposed hierarchical controls need not be developed from scratch. Rather, it can build on prior and current work funded by the DOE, including:

- A hierarchical optimization approach to dispatch building loads and DERs in coordination with distribution network reconfiguration to adapt to the propagation of faults and outages[13] (NREL)
- A resilient system dispatch tool, developed through DOE funding that can proactively define and dynamically cluster resilient microgrids and a framework, under development through the DynaGrid project, for dynamic formation and operation of microgrids to improve distribution system resilience. (NREL)
- Tools and algorithms from the Citadels project for networked microgrids (PNNL)
- Tools and algorithms from the Resilient Operations of Networked Microgrids (RONM) project (LANL), including restoration algorithms that incorporate networking of microgrids
- Tools, algorithms and restoration optimization approaches for black start of distribution grids developed through CleanStart DERMS project (LLNL)
- Tools developed in North American Energy Resilience Model (NAERM) project related to high-DER scenarios for threat/impact analytics to address the response of the grid and resilience during emergency conditions (LLNL)
- A decision support tool for early-stage, resilience-based designs for microgrids (SNL)

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[13] W. Liu and F. Ding, "Hierarchical Distribution System Adaptive Restoration with Diverse Distributed Energy Resources," in IEEE Transactions on Sustainable Energy, doi: 10.1109/TSTE.2020.3044895. https://ieeexplore.ieee.org/document/9295416

W. Liu and F. Ding, "Collaborative Distribution System Restoration Planning and Real-Time Dispatch Considering Behind-the-Meter DERs," in IEEE Transactions on Power Systems, doi: 10.1109/TPWRS.2020.3048089. https://ieeexplore.ieee.org/document/9310248

Section 6

Use-case / Scenario Examples

These use cases highlight how the concept of microgrid as a building block for the future grid can be used in the next 5-10 years as part of a larger strategy to enhance the utility of microgrid technologies. The vision would enable the grid to evolve from individual microgrids to networked microgrids, microgrids with varying boundaries, to a heterogeneous collection of individual and networked microgrids, to ultimately a grid of the future where the concept of grid-of-the-grids is realized—where microgrids serve as a building block for the future grid.

6.1 Use Case 1: Real-time operations under normal conditions

As a first use case, we consider real-time operations of a large-scale power system with very high DER penetration. This will demonstrate the effectiveness of the proposed hierarchical control structure under normal operating conditions, and how it addresses the challenges of applying advanced controls and optimization approaches to a large-scale power system with high DER penetration.

6.1.1 Large-scale simulation study

This use case is proposed to demonstrate the different approaches presented in this paper to realize the vision of a grid with microgrids as foundational building blocks using large-scale simulations of the distribution system of the San Francisco Bay Area illustrated in Figure 5. The overall system has more than 10 million electric nodes, with more than 4 million customers. Different DER penetration scenarios will be considered. At the extreme situation, with each customer having several controllable DERs, this leads to millions of control points.

A very high penetration scenario previously developed at NREL for the Autonomous Energy Systems study will be leveraged, which also includes a demonstration of a basic hierarchical control framework[14]. To model the distribution network, the synthetic models developed by the ARPA-E SmartDS project[15] will be used. These models have more than a million nodes across 264 feeders. These feeders can be partitioned into cells and microgrids as described earlier. Using the concept of microgrids as building blocks for the overall grid, this large-scale simulation will demonstrate scalability of computations and control under normal grid conditions. This use case can also be extended to abnormal operations, implementing extreme disruption scenarios such as hurricanes, wildfire, and earthquakes.

[14] B. Kroposki, A. Bernstein, J. King, D. Vaidhynathan, X. Zhou, C. Chang and E. Dall'Anese, "Autonomous Energy Grids: Controlling the Future Grid With Large Amounts of Distributed Energy Resources," IEEE Power and Energy Magazine, Vol. 18, Issue 6, Nov/Dec 2020

X. Zhou, Z. Liu, W. Wang, C. Zhao, F. Ding, L. Chen, ``Hierarchical Distributed Voltage Regulation in Networked Autonomous Grids'', American Control Conference, 2019

[15] V. Krishnan, B. Palmintier, B. Hodge, E. Hale, T. Elgindy, et al., "Smart-DS: Synthetic Models for Advanced, Realistic Testing: Distribution Systems and Scenarios". https://www.osti.gov/servlets/purl/1375108.

A small-scale deployment of the hierarchical controls developed for the Autonomous Energy Systems study was completed at the Basalt Vista neighborhood in the Holy Cross Energy's service territory[16] in Colorado in 2019. Four all-electric townhomes were used for the demonstration. In each home, DER controllers were installed to control rooftop PV, battery energy storage, EV charger, air conditioning load and electric water heater load, respectively. A coordinated controller was installed at the service transformer of these four homes to coordinate the operations of local DER controllers. Through such hierarchical control, the experiments have demonstrated that coordinated operations of DERs can mitigate reverse power flow and overvoltage issues, and also can help each building or the community to operate as a grid-connected microgrid. There is also a pilot, the California Energy Commission-funded Oakland EcoBlock project[17], underway in the San Francisco Bay area where the utility plans to enable sectionalizing a short, single-phase 2.7-kV (line-to-neutral) lateral distribution feeder and operating it as an island during grid outages. This could be potential pilot site for the proposed control algorithms.

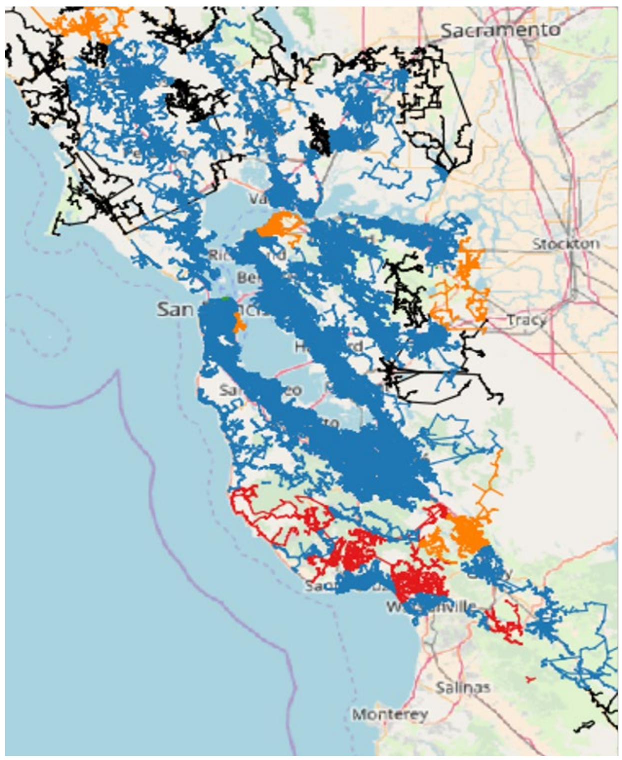

Figure 5 – San-Francisco Bay Area Distribution Network

6.1.2 Pilot deployment

This use case is proposed as a potential early pilot demonstration site for the proposed vision of microgrids as building blocks. As part of a Cooperative Research and Development Agreement, Emera Technologies and Sandia National Laboratories have installed a single-bus (+/- 375 VDC), ten-node 250kW hybrid DC/AC hybrid microgrid on Kirtland Airforce Base (KAFB) that links together generation and load at Kirtland and Sandia facilities (Figure 6). The microgrid has been autonomously operational since December

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[16] https://www.nrel.gov/news/features/2019/small-colorado-utility-sets-national-renewable-electricity-example-using-nrel-algorithms.html

[17] https://ecoblock.berkeley.edu

2019 and is supplying power to a variety of different AC residential and critical loads, including a community center (node 7), military housing (node 1-6) and a community laundromat (node 8). A community energy park (node c1) has commercial-scale PV generation, backup natural gas generation and connection to the MV AC grid. The microgrid has demonstrated grid-connected operation, autonomous islanded operation, system blackstart, and renewables incorporation of 100% peak load (140% average penetration).

Figure 6 - Installed and operational DC/AC hybrid microgrid on Kirtland AFB. This Sandia/Emera project has been operational since December 2019

The DC microgrid on KAFB is a hierarchical microgrid in that is composed of modular, repeating blocks that can operate as independent microgrids or collaboratively to form a larger microgrid. This is enabled by power electronic interfaces at each interconnection, known as a "power block" – a modular power electronics-based interface that contains power conversion, control, protection, and storage. These modular "power blocks" are themselves their own nanogrids with control, storage, generation, and load. Multiple nanogrids can then be connected on a common bus to form a microgrid. These microgrids, in turn, can be interconnected to the bulk power system (BPS) and/or interconnected to each other to form a grid of microgrids (Figure 7). Each power block is a self-contained unit which can store energy, provide either DC or AC load, and import/export power to the microgrid. This allows flexible deployment of microgrids that are interoperable and connected.

This specific hierarchical topology utilizes a number of innovations that enable rapid scale-up to larger interacting microgrids. The use of a modular power electronics-based "power block" at each node enables:

- flexibility to incorporate a variety of DER allowing for the most effective solution to be implemented at each node
- each node to be discretely controllable, enabling granular control of power in resiliency scenarios so that available power can be provided specifically to critical infrastructure
- scalable microgrid topology, as the "power block" is both modular and hierarchical, allowing for extension of the microgrid to power requirements as needed through the addition of nodes on a common bus or additional buses
- operation of the microgrid in a post-and-bid hierarchical control scheme, allowing for a central dispatch from a utility or other operator, aggregating block homes and block communities while maintaining stability at each node

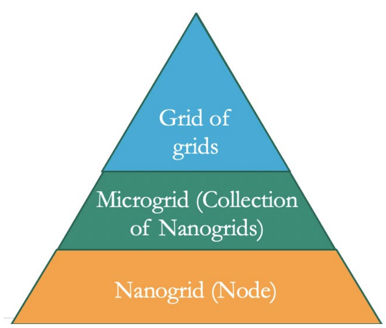

Figure 7 - Hierarchical structure of the microgrids operating on KAFB. Layer can operate independently, or collaboratively between layers since each layer has dedicated control, load, and generation

The first two levels of the hierarchy have been deployed and demonstrated at KAFB as of December 2019. Future work is directed to deploying the topology to multiple, interacting microgrids that utilize KAFB resources.

6.2 Use Case 2: Real-time operations under emergency conditions

As a second use case, we consider the impact of a shift to the vision of a grid with microgrids as building blocks on grid operations under planned and unplanned outages due to weather and/or fire events.

6.2.1 Planned outage use case for wildfires

California has experienced unprecedented wildfire activity levels in the past three years. These include the well-publicized "Camp Fire" that destroyed the town of Paradise and the Santa Rosa fire which destroyed major parts of the city of Santa Rosa. A root cause of these events is a confluence of ignition point or the spark that the utility equipment would provide to start the fires, vegetation management challenges, state versus federal zoning, aging equipment, extreme weather events (both heat, wind, and storms), and maintenance delays. In response to these deadly fires, PG&E has created a new program called the Public Safety Power Shutoff (PSPS) strategy, where the utility identifies high risk areas, specifically during high temperatures and red flag wind events, using overlays of vegetation and wind projections with existing power infrastructure. SCE has mirrored this program in southern California.

When a PSPS is invoked, a utility proactively de-energize any power lines at risk. "Resilience zones" have been proposed in the PG&E region, particularly where the *at risk* area is the primary transmission line, not the local distribution feeder. The resilience zones would essentially become transient microgrid areas. Many methods are proposed for this, from the most basic level (diesel generators) up to collaborative aggregation techniques for using local DER, and all combinations in-between. During these outages, the number of backup generators purchased by utility customers is significant and could be useful to create ad-hoc microgrids to support the resilience zone microgrids. Resilience zone microgrids will have grid-forming inverter-based DERs in addition to the traditional diesel generation to enable blackstart of the microgrids. The advantages of solar PV over diesel in this context include long-term viability independent of fuel delivery, and reduced potential of (ironically) adding to fire hazards. One example of recent microgrids upgrades motivated by increased resiliency, including wildfire risk, is at Anza Electric Cooperative (EC)[18]. Anza EC is a distribution cooperation in Anza, California who receives its wholesale power over a single radial 32.5 kV transmission line. This transmission line crosses U.S. Forest Service land and is responsible for three-quarters of the co-op's outages, including a ten-day outage in 2018 due to a wildfire. Motivated by deferring capacity upgrades to this transmission corridor, and increased resiliency during line-outages, Anza have recently installed a 2MW/4MWh lithium-ion solid state battery, 1.4MW PV system and microgrid controller. This solar-plus-storage microgrid was identified as the most cost-effectiveness solution.

Resilience zone microgrids would form the building blocks of larger grids—the neighboring resilience zone microgrids can be networked to provide grid services and blackstart support to each other, or they can merge into each other to form larger microgrids. This paradigm will perfectly fit the vision of microgrid as a building block of future grids or grid-of-the-grids during planned outage scenarios. During situations such as these when loss of power and communications is a significant challenge, microgrids will help with resilience of the distribution grids during outages.

6.2.2 Extreme weather event use case

This use case is proposed to demonstrate the performance of a power system with microgrids as building blocks when subjected to a severe weather event, using power system in Texas as an example. The state of

[18] NRECA (2021) The Value of Battery Energy Storage for Electric Cooperatives. January 2021, Business & Technology Report.

Texas is vulnerable to extreme weather events that impact electric grids not only by physically damaging infrastructure, such as hurricanes, but also by creating simultaneous conditions of high electric demand and supply shortages, such as was experienced in February 2021 during an extreme cold spell. While much can be said about planning for resource adequacy, the possibility of miscalculation in the face of shifting climate is a reality.

This use case will provide a realistic extreme weather scenario based on the effects of Hurricane Dolly on the Texas electric grid (July 20-27, 2008). Figure 8 shows the path of the hurricane and the Texas transmission grid.

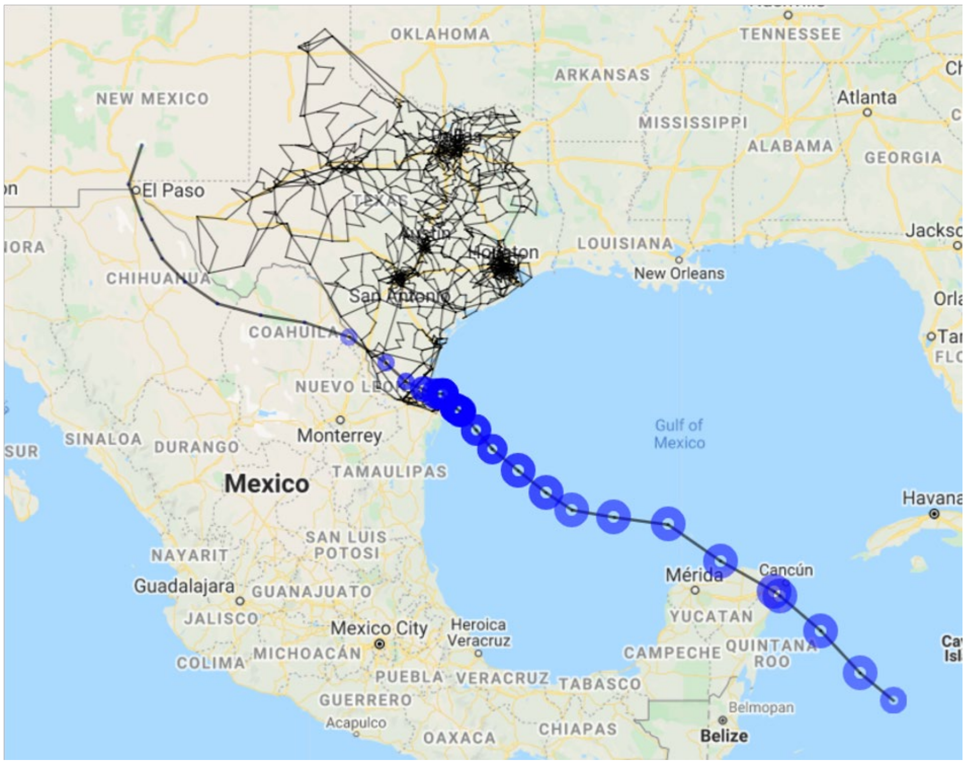

Figure 8 - Path of the Hurricane Dolly (July 20 -27, 2008) and synthetic TAMU 2000 bus transmission grid. Size of the blue circles corresponds to hurricane's radii and their color intensity correspond to maximum wind speed.

Simulations of the damage to the power systems in Texas, developed through NREL's LDRD funding, under the Resilience Science[19] project, will be leveraged. The scenario includes modelling the wind damage to electric infrastructure (generators, lines, substations) using fragility curves. The transmission grid is modelled using the synthetic data from Texas A&M (TAMU grid). The distribution system will be modelled using either standard IEEE test feeders, or synthetic data from the ARPA-E Smart DS project and the feeders will be modified to reflect a high DER-penetration future system. The feeders will then be partitioned into cells and microgrids and the control approaches proposed in this paper will be applied. This use case will demonstrate how the architecture and approaches proposed in this paper can improve the resilience of the grid during major natural disasters.

[19] M.K. Singh, G. Cavraro, A. Bernstein, V. Kekatos, ``Ripple-Type Control for Enhancing Resilience of Networked Physical Systems,'' American Control Conference, 2021

Section 7

Research Targets and Goals for 5 to 10 Years

Several new technology developments are required to realize the vision set out in this white paper, as described in Section 3. This section sets out in more detail the research and development needs for those developments and identifies gaps that need to be addressed between the current state of the art and technologies under development as described in Section 4. A more comprehensive roadmap should be devised by a cross-laboratory team with input from academia and industry—through workshops—within the first 18 months of this effort to further refine the research and development work to be performed.

A key area of research is the development and maturation of distributed control and optimization capabilities to support the proposed vision. These controls should be able to optimally operate a grid—under normal and emergency conditions—that is comprised of DERs and loads organized into cells and microgrids with dynamic boundaries. For cells to operate as microgrids, cell-level controllers that meet the requirements set out for microgrid controllers in IEEE 2030.7, including managing islanding and reconnection transitions, dispatch and steady-state voltage and frequency regulation, will be required. Many different control approaches may be utilized for cell-level and higher levels of control, but these should incorporate the latest advances in data analytics, machine learning, and artificial intelligence, where applicable.

Research towards such an architecture has been recently carried out in several national labs and universities. One example is a control framework that has been developed under the Autonomous Energy Systems (AES)[20] program at NREL, leveraging input and feedback across industry and academia through a series of workshops[21]. The AES control framework development has so far mainly focused on operations under normal grid conditions. To address emergency conditions, a resilient system dispatch tool has been developed through LDRD funding that can proactively define and dynamically cluster resilient microgrids, and a framework is under development through the OE DynaGrid project for dynamic formation and operation of microgrids to improve distribution system resilience.

Major remaining gaps that need to be addressed include:

- **Distributed microgrids reconfiguration**: How to incorporate the dynamic reconfiguration solutions within the hierarchal control framework to allow microgrids to reconfigure without the need for a centralized controller?
- **Real-time operation with dynamically reconfigured system**: Demonstrate the efficacy of hierarchal control approaches when applied to a dynamically reconfigured system using supporting theoretical studies and simulations.
- **Electric transportation**: How can microgrids be formed and controlled dynamically to adjust to the time-varying nature of fleets of electric vehicles and other electric transportation (e.g., trucks,

[20] https://www.nrel.gov/grid/autonomous-energy.html; B. Kroposki, A. Bernstein, J. King, D. Vaidhynathan, X. Zhou, C. Chang and E. Dall'Anese, "Autonomous Energy Grids: Controlling the Future Grid With Large Amounts of Distributed Energy Resources," IEEE Power and Energy Magazine, Vol. 18, Issue 6, Nov/Dec 2020 and X. Zhou, Z. Liu, W. Wang, C. Zhao, F. Ding, L. Chen, ``Hierarchical Distributed Voltage Regulation in Networked Autonomous Grids'', American Control Conference, 2019

[21] https://www.nrel.gov/grid/autonomous-energy-grids-workshop.html (September 2017); https://www.nrel.gov/grid/innovative-optimization-control-methods.html (April 2019); https://www.nrel.gov/grid/workshop-autonomous-energy-systems.html (August 2020)

trains, buses)? How to dynamically co-optimize transportation and power networks to alleviate traffic congestions in the former, and improve overall efficiency and resilience in the latter.

- **Interdependent utility networks**: How microgrids can be formed and controlled dynamically to take into account the operation and constraints on gas and water networks?
- **Human-in-the-loop**: How to incorporate people's preferences and equity aspects in the control framework, emphasizing the role of disadvantaged communities; and how to account for adversarial human behavior in the system?
- **Asynchronous operation**: Most of the distributed methods rely on the fact that controllers act in a synchronous fashion. Achieving synchronization is possible in simulation environments or in small-size networks, but hard, if not impossible, in large-scale systems with heterogeneous controllers with different sensing, communication, and control rates. Hence, it is critical to advance the foundational science behind asynchronous control and estimation algorithms, enabling the practical implementation of advanced control and monitoring platforms in utilities and aggregators.
- **Data-driven/model-free methods:** The existing methods typically require accurate model information; however, in reality, these controllers might not be able to acquire accurate network model and real-time measurements due to communication loss or delay caused by outages or extreme events. This challenge could be addressed by incorporating topology estimation, machine learning approaches and model-free control techniques.
- **Behind-the-meter information**: How to integrate behind-the-meter DER information and flexibility into utility operation system, and how to protect customer privacy and consider occupant preferences to encourage the participation of behind-the-meter flexibility.

Implementation of a distributed control framework will also require distributed, cyber-secure communications—including peer-to-peer—capabilities and advanced, interoperable sensors that should incorporate data privacy preservation. Research targets related to some of these are discussed in the Topic 5 white paper.

Systems with very high DER penetrations will require greater flexibility in loads to offset the need for storage. Therefore, optimization approaches that enable increased involvement of customers in demand side management through dispatching building loads and DERs in a coordinated way will be needed. This will require higher resolution load forecasting that uses machine learning approaches. Additionally, distribution network reconfiguration algorithms to adapt to the propagation of faults and outages, and that can dynamically form microgrids, will be needed. These should be able to distinguish, prioritize and selectively serve critical loads. Some work has been done on network reconfiguration, including algorithms and restoration optimization approaches for black start of distribution grids using DERs through the CleanStart DERMS project[22]. Work is also under way on restoration algorithms that include individual and networked microgrids through the Resilient Operations of Networked Microgrids (RONM) project, and on hierarchical optimization approach to dispatch building loads and DERs in coordination with distribution network reconfiguration to adapt to the propagation of faults and outages[23] through LDRD funded projects.

In order to deploy these controls, optimization and network reconfiguration approaches in the field, upgrades to utility management systems, such as advanced distribution management systems (ADMS) will be needed, especially the ability to host distributed, hierarchical controls. The OE-funded, open-source

[22] https://gmlc.doe.gov/projects/1.5.05

[23] W. Liu and F. Ding, "Hierarchical Distribution System Adaptive Restoration with Diverse Distributed Energy Resources," in IEEE Transactions on Sustainable Energy, doi: 10.1109/TSTE.2020.3044895. https://ieeexplore.ieee.org/document/9295416

W. Liu and F. Ding, "Collaborative Distribution System Restoration Planning and Real-Time Dispatch Considering Behind-the-Meter DERs," in IEEE Transactions on Power Systems, doi: 10.1109/TPWRS.2020.3048089. https://ieeexplore.ieee.org/document/9310248

GridAPPS-D platform[24] is being designed with this in mind and they have hosted several workshops on distribution ADMS applications to collect industry and academia inputs on what is needed, and these insights could be leveraged to enable industry to realize the vision. Utility management systems will also need monitoring and state estimation tools that can function effectively in a high-DER penetration system with microgrids, and the latest advances in data analytics and machine learning should be incorporated into developing these.

In addition to operational tools, planning tools will also need to be updated to account for the operational changes. Research targets for planning tools are described in the Topic 6 white paper. Specific planning tool needs to enable the vision for microgrids as building blocks include the ability to optimally place utility-owned DERs and sectionalizing switches to enable dynamic network reconfiguration and the formation of microgrids. Design of incentives from utilities and/or federal agencies to encourage placement of DERs at residential and/or commercial building sites that support the formation of microgrids should also be considered.

Advances in inverter controls, especially for grid-forming inverters, to address stability oscillation issues in low-inertia systems will also be needed. Grid-forming inverters that can provide black start services will also be needed. The DOE developed a road map[25] for grid-forming inverters that provides a list of research questions related to frequency control, voltage control, protection and fault ride-through.

Advances in protection coordination for networks with microgrids that can be operating in various combinations of grid-connected and islanded modes will be needed and research targets are laid out in the Topic 5 white paper for protection. A specific need to realize a grid with microgrids as building blocks is substation switches to accommodate feeder-level cells combining into a substation-level cell. Methods to design and adjust protection devices in coordination with network topology changes caused by network reconfiguration, such as incorporating adaptive protection settings, will also need to be developed.

All of these developments should be combined into development of full architectures for a grid with microgrids as building blocks. This should build on the foundational work performed under the GMLC Grid Architecture project[26], which has resulted in several reference architectures, including one for a high DER, distribution automation and storage future[27], such as what we consider here. These architectures should be proven first through large-scale simulations which can use power system models and damage scenarios previously developed, as described in the use cases. Additional use cases will require partnerships with industry to provide models and field data. The GridAPPS-D platform could be used to implement and demonstrate the viability of the proposed controls. These large-scale simulations could also be coupled with advanced hardware for realistic hardware-in-the-loop simulations to help de-risk field deployment of these new technologies. This should then be followed by a transition to field pilots that incorporate advanced controls, hardware and communications technologies.

Beyond the technology development requirements, there is also a need to ensure that a regulatory framework exists that can support the deployment of the proposed vision. The topic 7 white paper addresses these aspects, and there should be collaboration to ensure that considerations specific to the proposed vision is included, such as new billing rules to address a DER from one customer serving a different customer, and ensuring customer equity.

These developments should proceed along the following timeline over the next 5 to 10 years. Over the shorter term, i.e., the first three years, the focus should be on extracting learnings from currently funded

[24] https://www.gridapps-d.org/

[25] Y. Lin, J.H. Eto, B.B. Johnson, J.D. Flicker, R.H. Lasseter, et al, "Research Roadmap on Grid-Forming Inverters," https://www.nrel.gov/docs/fy21osti/73476.pdf

[26] J. Taft, " Grid Architecture," *IEEE Power and Energy Magazine,* Sep/Oct 2019. doi 10.1109/MPE.2019.2921739

[27] JD Taft, et al., "High DER/DA/STO Reference Architecture, GMLC 1.2.1 v0.3," December 2019. https://gridarchitecture.pnnl.gov/library.aspx

projects and developing a road map and grid architecture as well as funding opportunities for future work. In the medium term, over the 3 to 5-year horizon, new projects should be funded to address remaining gaps, and in the long term, 5-10 years, the focus should turn to pilot demonstrations in partnership with utilities and technology transfer to industry to set the foundation for longer-term changes.

1-3 years:

- Design and demonstrate networked microgrids in simulation and pilot projects through completion of the GMLC Citadels project (PNNL) and the Resilient Operations of Networked Microgrids (RONM) project (LANL), as well as projects to interconnect isolated microgrids in Alaska. These projects are addressing challenges such as cold load pickup with dynamic microgrid boundaries, restoration algorithms that make use of microgrids within a network, and protection for microgrids with dynamic boundaries within a distribution system with multiple different configurations.
- Develop a roadmap to enable a move from a centralized to a distributed paradigm by demonstrating current-generation hierarchical controls and dynamic microgrid formation during extreme events through simulation of one or more use cases. This should consider the costs that will be associated with this paradigm shift.
- Develop a draft architecture specification for a grid with microgrids as building blocks. Consider interplay between interdependent infrastructure systems, in particular:
    - Electric transportation: How microgrids can be formed and controlled dynamically to adjust to the time-varying nature of fleets of electric vehicles and other electric transportation (e.g., trucks, trains, buses).
    - Water and gas network: How microgrids can be formed and controlled dynamically to take into account the operation and constraints on those networks.
- Issue a call for proposals for projects in the 3-5 years phase to address the gaps identified in the roadmap and that are consistent with the architecture specification.
- Provide input to the regulatory roadmap development proposed under Topic 7 that identifies the additional changes required in regulatory and business practices to allow the implementation of the proposed future vision.

3-5 years:

- Mature the technology and tool developments from the networked microgrid projects, including protection, control and communication technologies through additional pilot demonstrations and simulations.
- Implement the roadmap to move from networked microgrids to advanced architectures that encompass merging of neighboring microgrids, dynamic boundaries for microgrids, DERs and fleet of DERs providing services to the bulk power system.
- Design advanced protection, next-generation control algorithms and communications and demonstrate through large-scale co-simulation.
- Develop final architecture specification for a grid with microgrids as building blocks.
- Engage regulatory entities to lay groundwork for pilot deployments of grids with microgrids as building blocks.

5-10 years:

- Move toward distributed control and communication, where multiple cells interact with each other in a distributed fashion through pilot implementations of distribution grids with microgrids as building blocks.

- Work on technology transfer to ensure this work does not only end in pilot projects but in actual products and solutions from the private sector, e.g., through start-ups or collaboration with existing vendors.

Section 8

Why Should DOE be Funding these Goals and Visions

The topic of microgrids as a building block for future grids is ideally suited for DOE funding because it is developing the architectural foundation for a future grid that is secure and resilient. It is vital to national and economic security to ensure that the most critical energy infrastructure is able to recover rapidly from disruptions[28]. The realization of the proposed vision will require development of new technologies and DOE can help accelerate these developments and reduce the risks associated with the adoption of these new technologies.

The current generation of industry is focusing on building the components of microgrids such as DERs and responsive loads, their management systems, and control and communication technology that enables a microgrid. Networked microgrids, which is a first step to using microgrids as a building block, is still in an early R&D phase with some pilots coming online through DOE-funded projects in the next couple of years. Different microgrid installations likely will use different technologies and vendors, and interoperability among the microgrids is a topic that will need to be addressed, and DOE can play a strong convening and enabling role in such an effort as a leading R&D funding agency supporting research on the topic of microgrids[29].

The value that microgrids provide as a building block will need to be articulated, especially for disadvantaged communities[30], so that the vision of grid-of-the-grids is realized to the fullest extent. This provides DOE a unique opportunity to take the lead and lay out the vision of the benefits of the architecture that builds upon a foundation supported by microgrid technology. By continuing to invest in articulating the vision of microgrids as a building block for future grids, DOE can ensure that microgrids are an integral part of future operations—both at distribution and bulk grid levels—providing flexibility and resilience to the nation's electrical infrastructure.

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[28] https://www.energy.gov/oe/mission

[29] https://energycommerce.house.gov/sites/democrats.energycommerce.house.gov/files/documents/Section-by-Section%20of%20CLEAN%20Future%20Act%20117th.pdf

[30] https://www.whitehouse.gov/briefing-room/statements-releases/2021/01/27/fact-sheet-president-biden-takes-executive-actions-to-tackle-the-climate-crisis-at-home-and-abroad-create-jobs-and-restore-scientific-integrity-across-federal-government/

Section 9

Review Committee

Caltech:	Steven Low
DTE:	John O'Donnell
Holy Cross Energy:	Bryan Hannegan
NRECA:	Emma Stewart
PG&E:	Alex Portilla
Siemens:	Ulrich Muenz