U.S. DEPARTMENT of ENERGY

DRAFT REPORT

Microgrids R&D Strategic Plan

Topic 3 – Building Blocks for Microgrids

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Disclaimer

Original Authors

The authors of the original 2021 document that formed the basis for this iteration are:

Chen-Ching Liu, Virginia Polytechnic Institute and State University (VT)

Madhu Chinthavali, Oak Ridge national Laboratory (ORNL)

Rob Hovsapian, Savannah River National Laboratory (SRNL)

Hannah Burroughs, Lawrence Livermore National Laboratory (LLNL)

Sigifredo Gonzales, Sandia National Laboratories (SNL)

Frank Tuffner, Pacific Northwest National Laboratory (PNNL)

Miguel Heleno, Lawrence Berkeley National Laboratory (LBNL)

Ravindra Singh, Argonne National Laboratory (ANL)

Adam Mate, Los Alamos National Laboratory (LANL)

Dush Boyoyevich, VT

Herbert Ginn III, University of South Carolina

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Revision Authors

The authors of the 2025 revision to the strategy document are:

Chen-Ching Liu, VT

Baza Somda, VT

Rob Hovsapian, SRNL

Sanjeev Pannala, National Laboratory of the Rockies (NLR)

Yashodhan Agalgaonkar, NLR

Joao Onofre Pereira Pinto, ORNL

Alok Kumar Bharati, PNNL

List of Acronyms

AI	Artificial Intelligence
BOS	Balance of System
CHP	Combined Heat and Power
DOE	U.S. Department of Energy
LC	Load Controller
LEL	Large Electric Loads
MBB	Microgrid Building Block
MG	Microgrid
MGC	Microgrid Controller
ML	Machine Learning
MPS	Modular Power Sources
OE	(U.S. DOE) Office of Electricity
O&M	Operation and Maintenance
PCC	Point of Common Coupling
PEBB	Power Electronics Building Blocks
POC	Point of Connection
R&D	Research and Development
RD&D	Research, Development, and Deployment
SMR	Small Modular Reactor
SSPS	Solid State Power Substation
SST	Solid State Transformer
T&D	Transmission and Distribution
TA	Technical Assistance

Executive Summary

Microgrid Building Blocks (MBB) technologies will enable potential applications in emerging load growth centers that are distributed widely across different states, particularly from large loads such as data centers/AI workloads, critical mineral mining and extraction operations, and industrial facilities across various sectors. MBB technologies can enhance the reliability of data center loads by riding through diverse grid events, including both utility-side disturbances and internal faults in on-grid and off-grid settings. They also offer affordable solutions to end customers by co-locating these emerging loads near available generation resources, thereby reducing infrastructure upgrade costs and mitigating prospective interconnection challenges and processes. Further, MBB can standardize the microgrid configurations to boost the quick adoption of grid connected to islanded mode of operation for reliable supply to emerging large loads and industrial customers.

For practical deployment of MBB technologies, partnership with industry, national laboratories, and academic institutions are important to take advantage of the best talents and available resources. Future commercialization of MBB-based technologies will require field testing and validation from power grids, especially distribution utility systems.

Rapid growth in data centers, AI computing infrastructure, critical mineral mining, and advanced industrial facilities is placing unprecedented stress on distribution and transmission systems. These emerging load centers are geographically dispersed across multiple states, exhibit highly dynamic and transient load profiles, and demand exceptionally high levels of power quality, reliability, and resiliency. Traditional grid infrastructure and planning paradigms are increasingly challenged to meet these requirements in a timely and cost-effective manner.

MBB technologies provide a natural and scalable solution to these challenges by enabling standardized, interoperable, and resilient microgrid architectures tailored for large, mission-critical loads. For data centers and AI workloads, MBB-enabled microgrids enhance power quality and operational continuity by mitigating voltage and frequency disturbances, reducing the impact of capacity fluctuations, and enabling seamless ride-through of both utility-side events and internal faults. This capability is essential for maintaining uninterrupted operations, protecting sensitive computing equipment, and ensuring service-level commitments in grid-connected and off-grid operating modes.

In mining and industrial applications, where loads are often located at the edge of the grid or in remote regions, MBB-based microgrids provide reliable and affordable energy access by co-locating loads with available generation resources. This approach minimizes costly grid upgrades, accelerates interconnection timelines, and enables stable operation despite highly variable and motor-dominated load profiles. The standardized and modular nature of MBBs further supports rapid transition between grid-connected and islanded operation, ensuring continuity of supply during extreme events, grid outages, or planned maintenance.

Beyond technical performance, MBB technologies reduce overall system costs and deployment risks by standardizing microgrid configurations, protection schemes, and control interfaces. This standardization accelerates adoption across diverse sectors, simplifies engineering and integration efforts, and supports replication at scale across multiple sites and jurisdictions.

Successful deployment and commercialization of MBB-based microgrids will require close collaboration among industry, national laboratories, utilities, and academic institutions. These partnerships enable access to best-in-class expertise, advanced testing infrastructure, and high-fidelity validation platforms. Field demonstrations and utility-integrated validation on real distribution systems are critical next steps to de-risk the technology, demonstrate operational and economic benefits, and enable widespread adoption of MBB-enabled microgrids to support the nation’s rapidly evolving large-load energy landscape.

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1 Introduction

Microgrids are envisioned to play an important role in the future energy infrastructure of the United States and its territories as they can enable solutions for largescale deployment of large electric loads in remote locations, provide energy solutions for applications like mining of critical materials that may be in remote isolated locations, etc. The microgrid building blocks (MBB) concept's primary goal is to standardize the equipment and controls for energy generation, distribution and consumption that can operate together as a microgrid in a stable and optimal manner that can accelerate the deployment of microgrids. The MBB concept also enables competitive markets for this technology which not only can drive affordability through economies of scale but also can enable growth in the future.

The concept of building blocks for microgrids (MGs) is essential for modular design and implementation and enhances reliability and cost-effectiveness. Microgrid Building Blocks (MBBs) integrate the main functions of a microgrid into a hierarchical structure. The first MBB workshop in 2019, hosted by Virginia Tech with participants from Department of Energy (DOE) and national labs, proposed MBB functions and requirements. The proposed MBB functions include power conversion, microgrid control, protection, islanding and reconnection, and storage. The MBB requirements include stability, interoperability, security, and scalability. To achieve the goal of modular design, it is important to develop a simplified approach to the design and implementation of a microgrid from the users' point of view. Here the users include power grids as well as industries, commercial entities, and communities that require reliable and resilient electricity service through the deployment of microgrids.

1.1 Key Blocks of the MBB Concept

To achieve a modular development approach, an MBB can be created to integrate the primary functions of power conversion and switching (with the utility grid and/or other microgrids) as well as microgrid communication and control. This integration simplifies the microgrid design. Indeed, a user who is interested in developing a microgrid has available generation resources, such as distributed generation assets, and energy storage devices. The user also has a set of electrical loads that will be served by the microgrid, which will sustain service to critical load when the utility system becomes unavailable due to extreme weather conditions or other events. MBB with power conversion and microgrid control/communication capabilities can be connected to generation/load components and control devices to form a microgrid. The design of the microgrid thus consists of three major tasks: MBB implementation, electrical system configuration, and communication and control system structure.

1.1.1 Microgrid Building Block (MBB)

As shown in Figure 1, the proposed MBB integrates the power processing, communication and control functions that may exist at a microgrid node and connects to other components in the microgrid or to other MBBs, through standardized power and communication interfaces. There is not a universal type of MBB; it will be customized to meet the needs for different application environments. Major microgrid components could each interface to the microgrid network through customized MBBs, e.g., sink-MBB for load clusters, source-MBB for generation and sinks/source-MBB for energy storage or to interface to the utility grid. The most straightforward example of an MBB is the integration of all substation functions at the Point of Common Coupling (PCC) of the microgrid to the utility grid. In such a simple form, the MBB has one Power Interface connected to the higher voltage utility grid and another Power Interface(s) connected to the lower voltage microgrid, in addition to the multiple Communication Interfaces to major microgrid components and to the SCADA system of the utility operator. The electromechanical Power Processing Functions include power transformers for voltage level adjustment and ground isolation, fault protection on both power interfaces, as well as various switchgear for disconnecting, re-closing, and reconfiguration.

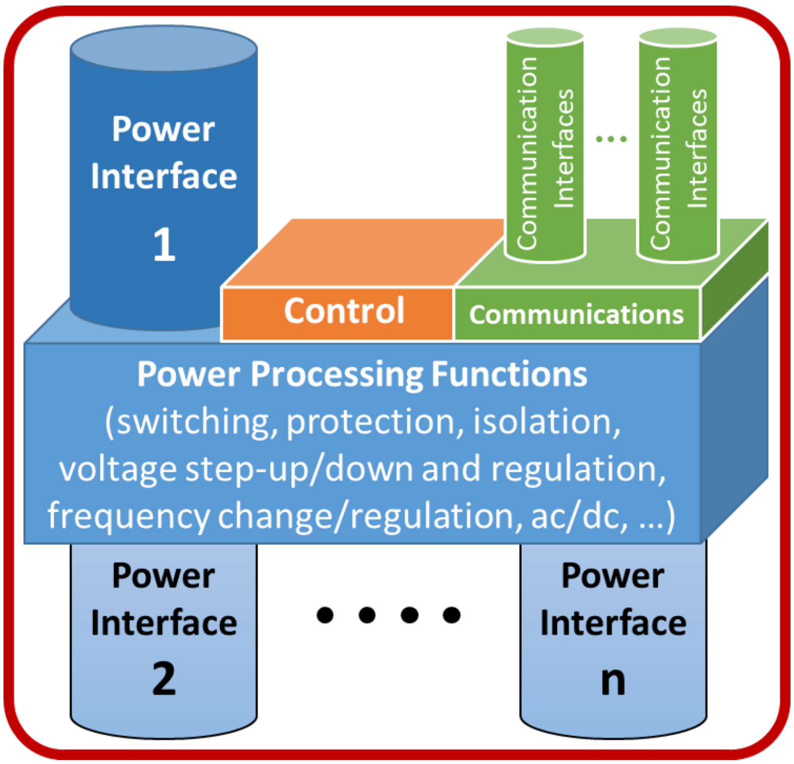


Figure 1: MBB with Power Processing, Communication, and Control Functions

The MBB incorporates a microgrid controller, which provides microgrid supervisory control such as voltage regulation using the microgrid distributed generation assets and demand response, as well as control the power processing inside MBB for islanding, resynchronization, reclosing, fault handling, and recovery, etc. Power conversion is bi-directional; hence, the power flow can come from the utility system and, in some scenarios, the microgrid can also serve power to the utility system through electricity trading arrangements if the microgrid is not owned by the same utility company. More complex microgrids can also incorporate variable-frequency AC and DC subsystems; in such cases, the power processing block must include power electronics converters with varying complexity of functions and controls, depending on applications. The major advantages of using power electronics converters include universality (increased flexibility) and re-programmability, significant size reduction, much smaller fault currents, etc., at somewhat increased costs and losses.

The generic architecture of the MBB concept is illustrated in Figure 2. There are specialized functions each block needs to perform. For example, the block on the far right, Power Transfer, interfaces with some form of external grid, such as another microgrid or the utility power system. This block needs to be able to communicate synchronization requirements to the overall MBB-based grid. It needs to be able to set a desired frequency and a voltage reference for the entire microgrid to operate smoothly with the external grid. This block is also responsible for executing the breaker or switch operation, or arming of a synch-check relay, when reconnection is desired and feasible. Another example of specialized capability, the “Sink Node” and the “Sink & Source Node” MBBs also require specialized controls. The MBB devices need to coordinate and represent any demand-response signals or direct controls to load devices connected.

The communication system serves data acquisition as well as control commands for the entire microgrid as a cyber-power system. The microgrid controller provides functions like those of a control center in a power grid. However, control commands can be issued from a remote location by system operators, or the commands may be autonomous within the microgrid. Communication can be wired, wireless, or a combination of both, depending on the microgrid environment. The centralized microgrid controller has the capability to calculate the appropriate control actions based on the data/information acquired from various nodes in the microgrid in a real time environment. In contrast, in a distributed control structure, software/hardware agents at different nodes share data/information and collaborate in the control tasks.

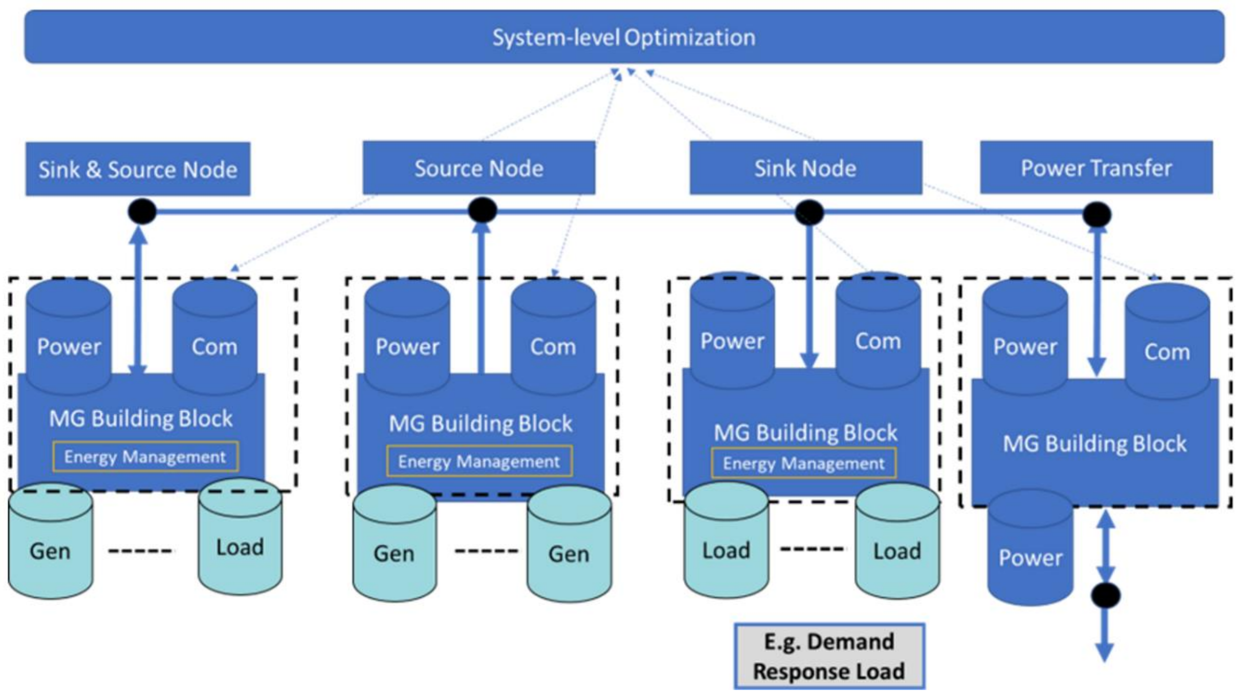


Figure 2: Typical Microgrid Building Block (MBB) Based Architecture

1.1.2 Electrical System Configuration

As shown in Figure 1, each MBB has two or more Power Interfaces that connect the power processing inside the MBB to the outside world. The Power Processing Functions include switching and reconfiguration, fault protection on all Power Interfaces, isolation, voltage step-up/down, voltage regulation, frequency synchronization, and could include frequency change and regulation, as well as AC to DC conversion, or vice versa, if power electronics conversion is used. MBBs power terminals should have standardized Power Interface connectors and ratings to simplify microgrid construction and operation.

Traditionally, distribution system protection is provided by circuit breakers and protective relays in the substations as well as reclosers and fuses installed on the primary feeders and laterals served by the primary feeders. Microgrids connected to a utility distribution system are no longer a radial system as there are multiple generation sources to serve the load. As a result, protection design for radial configurations is not effective. Instead, protection schemes and/or relays can be used to detect a fault on an electrical component (or a group of components) and isolate the faulted portion of the microgrid, allowing loads in other portions of the microgrid to be restored quickly with the available generation resources. The faults involving distributed energy supply and demand assets will necessitate coordination with the power-electronics-based resource control algorithms. Due to different short circuit currents and electrical behaviors, protection for a microgrid operating grid connected as part of the electrical system differs from protection for an islanded microgrid.

1.1.3 Communication and Control System Structure

The stable operation of a microgrid is dependent not only on the performance of the control system but also on reliability of the communication or cyber system on which the control signals are routed. A good cyber system must be robust, reliable, and secure. To design a realistic cyber model, three pieces of information are needed: cyber elements of the network, topology of these cyber components, and technology that could model these cyber elements. The cyber elements of a microgrid are the devices involved in communication or remote control. These may include the microgrid controller (MGC), local controllers (LCs), and the PCC. The communication structure among the cyber elements determines the topology. In some microgrids, a centralized communication system is employed and the MGC acts as the brain of the microgrid. In such a system, a leader-follower architecture is preferred. In a distributed (de-centralized) system; however, LCs and other intelligent devices interact with one another directly. Thus, the cyber system is peer-to-peer. There can also be a hybrid approach with centralized and distributed control functions.

A hierarchical structure exists for a distribution system with multiple microgrids that may be standalone or networked. In the complex operating environment, a systems approach is needed for operation, communication, control, protection, and planning of microgrids. In this case, there are multiple MBBs in the system that require an appropriate centralized or decentralized communication and control structure (Figure 2).

Practical considerations of the overall control of the MGC and MBB devices must also account for event scenarios that result in the loss of communication. In this case, it is important that any MBB-related control has a form of fallback operation. When the coordination mechanism for systemwide communication and control is not available, the local controllers or local MBB device should be able to operate reliably but may be at a suboptimal state.

1.2 State-of-the-Art

MBB is a new technology concept for the development and implementation of microgrids some details are explained in the subsection 1.2.1. However, significant progress has been made over the last decades on the related technology of Power Electronics Building Blocks (PEBB)(Ericsen and Tucker 1998)(IEEE 2004)(IEEE 2011), and more recently on the Solid Sate Transformer (SST) (Li et al. 2023)(Huber and Kolar 2019), Solid-State Power Substation (SSPS) (US DOE 2020) and intergrid (Boroyevich et al. 2013) concepts.

The building block approach extends from power electronic control systems. The overall control of a power electronics system is achieved by arranging rudimentary control functions to produce the desired control. When the control functions of various types of power electronic systems are examined, a significant degree of common functionality emerges, irrespective of the target application. It is possible to define hierarchical control architectures for these systems using common interface definitions between control system divisions or layers. Such definitions enable the use of common designs for multiple applications and the use of commercially available electronics and communications modules allowing cost reduction in power electronics applications.

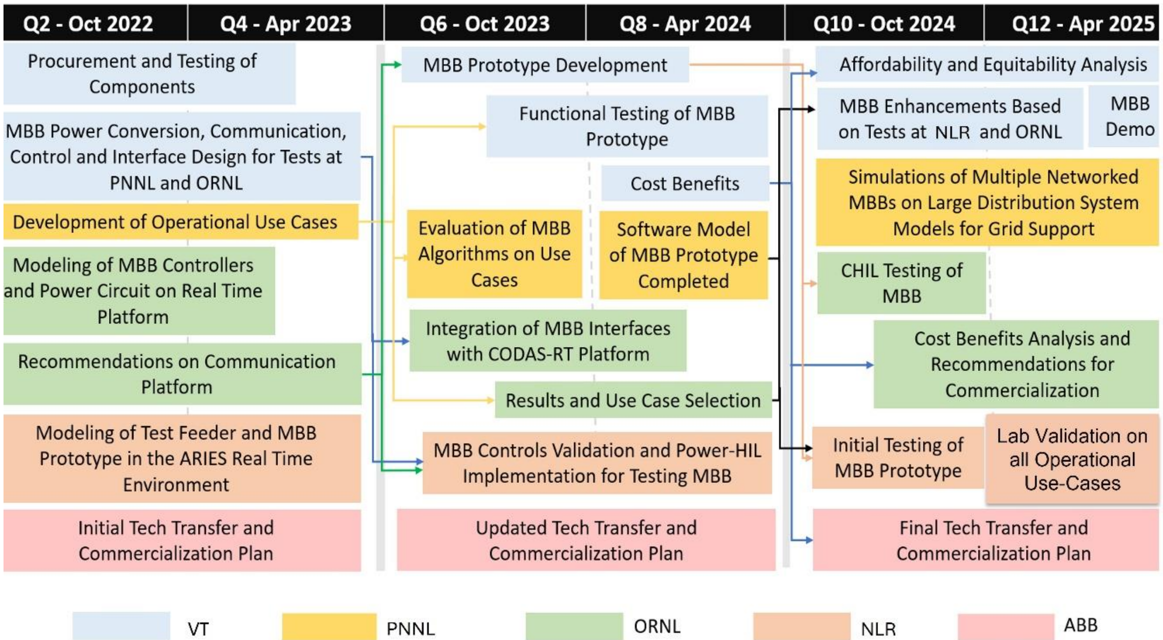
The Solid-State Power Substation (SSPS) idea, developed by the Advance Grid Research program in the DOE Office of Electricity, carries the PEBB concept further to address the electricity delivery network, especially for substations. In the roadmap document (US DOE 2020), SSPS is "defined as a substation or "grid node" with the strategic integration of high-voltage power electronic converters, [that] can provide system benefits and support evolution of the grid." The PEBB concept is clearly focused on modular implementation of power electronics converters, for any applications. However, PEBB and SSPS use exclusively power electronics converters for power processing functions, whereas MBB may use power electronics or more traditional electromechanical components or a combination of both, depending on specific needs and maturity of the underlying technologies. Additionally, SSPS sits only at the Power Transfer nodes between different sub-networks, while MBBs can additionally provide standardized interconnectivity of different generation (Source), storage (Sink/Source), and load (Sink) devices.

1.2.1 From Concept to Demonstration: Advancing Microgrid Building Block (MBB) Technology

A collaborative project[1], funded under the U.S. Department of Energy's Office of Electricity (DOE OE) Microgrid Program, was undertaken to design, develop, and test the key building blocks of the Microgrid Building Block (MBB) technology. The primary objective of this initial MBB project (Table 1) was to advance Recommendation R1 from the original MBB white paper (2021-2022) —moving the technology from a conceptual framework toward design, prototyping, testing/validation, and real-world demonstration. The MBB approach is envisioned as a foundational enabling technology for the widespread deployment of microgrids in the future grid environment. Its modular and standardized architecture can significantly reduce costs, losses, weight, size, and engineering effort associated with the application and maintenance of power electronics systems. Extensive modeling and simulation were performed to validate the MBB concept and transition it from theory to practical implementation.

[1] https://ece.vt.edu/content/dam/ece_vt_edu/research/power-energy-center/MBB_Presentation.pdf

Table 1: Completed MBB Project Milestones



Key accomplishments of the project include:

- *Prototype Development and Testing:* Hardware and software prototypes of the MBB were designed, built, and tested at Virginia Tech (Liu et al. 2023)(Somda et al. 2024).

- *Modeling and Simulation:* PNNL developed MBB-based microgrid models in GridLAB-D and conducted system-level simulations, including use cases demonstrating MBB's core capabilities (Mahmood et al 2024)(Acharya et al. 2024a)(Acharya et al 2024b).

- *Communication and Interoperability:* ORNL provided recommendations on communication platforms and developed a protocol translator to ensure interoperability. MBB capabilities were further validated through Controller Hardware-in-the-Loop (CHIL) testing (Adib et al. 2024)(Choi et al. 2024).

- *Integration and Demonstration:* MBB technology was integrated, validated, and demonstrated at NLR using the ARIES platform (Seo et al. 2025)(Chanda et al. 2024).

- *Cost-Benefit Analysis:* A detailed assessment quantified cost reductions achievable through modularization and standardization, along with qualitative benefits in operational savings (Qi et al. 2024).

- *Commercialization Strategy:* ABB developed a commercialization and technology transfer plan to guide market adoption.

The remainder of this strategy document is organized as follows. The vision of future MBB development is discussed in Section 2. Based on the vision, the roadmap for the MBB technology development is presented in Section 3. The future of MBB development will depend on the cost-benefits and use cases of MBB; a discussion of these topics is given in Section 4. Related enabling technologies that are available for MBB development are summarized in Section 5. Finally, based on the findings of this study, our recommendations of the future R&D to the DOE are stated in Section 6.

2 Vision for the Future

Microgrids have existed on geographical islands and in the Arctic region over the past century. A key ability is to withstand harsh operating conditions and provide reliable electricity which led to widespread constructions in numerous inland locations, where connection to bulk energy systems may not be available. By now, microgrids are found all around the world: from remote villages in Alaska to community microgrids in many Asian and European countries, and from islands surrounding Australia to military bases in the United States (Kimber et al. 2021)(Wild et al. 2016)(Pratt and Bialek 2019)(Marnay et al. 2015). With the growing interest in creating interconnected microgrids that can island and retain operation during disturbances, methods are being developed to seamlessly island towns as their own microgrids operate autonomously (Farrokhabadi et al. 2020)(Hoffman and Carmichael 2020).

To further advance the deployment of microgrids for increased reliability, secure, and affordable supply for critical customers, Microgrid Building Blocks (MBB) must be designed to be modular. In a simple microgrid configuration, an MBB-based control block serves as an add-on to existing microgrid controllers, determining optimal dispatch commands, accounts for microgrid stability, ancillary services, etc., by providing frequency and voltage control signals to ensure stable and efficient operation. The control block can be deployed at the PCC; however, it is flexible in that any node that is enabled for implementation of the control block can serve as the microgrid control node. The MBB-based microgrid control system can be operated autonomously with the control software and communication support.

In a complex configuration, a distributed control system can be beneficial. In this case, multiple MBB control blocks can be deployed in several nodes that are enabled for installation of the control blocks. The control blocks work as a team to coordinate the operation and control tasks. In a multi-agent system architecture, each control block is an agent that makes control decisions for that node. Multiple agents are then coordinated to ensure that the system level objective is met. Importantly, in case of communication failures, the agents can revert to a decentralized control strategy that only relies on local measurements to stabilize the system. This feature of the modular blocks enhances resilience by maintaining a stable, albeit suboptimal, operating point.

A networked microgrid is a good example of a complex configuration. Multiple control blocks are deployed to control each microgrid as well as coordinate the operations among multiple microgrids. The key concept of modularity is that the same module of MBB control block is deployed with the addition of a coordination layer for these control blocks.

In addition to its modularity, flexibility, as well as reduced cost, the MBB concept further enhances its value for MGs by application of universal control architecture. Having a universal microgrid controller and building block approach can serve diverse technologies such as energy storage or fuel cells in both AC and DC-coupled architectures. The building block and a universal controller will simplify integration of these advanced devices in a tightly interconnected environment. Benefits of a building block approach include:

- Enhanced resiliency, reliability of interconnecting microgrids through electrical and communication connectivity,
- Holistic consideration of microgrid resiliency considering cyber physical threats for building block approach and universal controller,
- Improves maintainability, scalability for future expansion, and standardization for both power and control for rapid recovery and reduced downtime,
- Reduction in the balance of system (BOS) cost with standardization of the interfaces and interconnects, and
- Reduction of operation & maintenance (O&M) costs with advanced features such as online health monitoring, and cyber physical security.

An MBB can be viewed as a power conversion stage with input and output ports to which load devices or assets can be connected along with control and communication capability. Given that the operating power of an MBB can range from tens of kW to MW based on application, the architecture of MBBs should support cascading or paralleling of Modular Power Stages (MPS). MPSs can be considered as the fundamental building blocks of MBBs. To support interoperability, scalability, and plug and play capability, both the MBB and MPS are designed with communication, control, intelligence, advanced algorithms, and protection. The vision of MBB development is summarized in Figure 4.

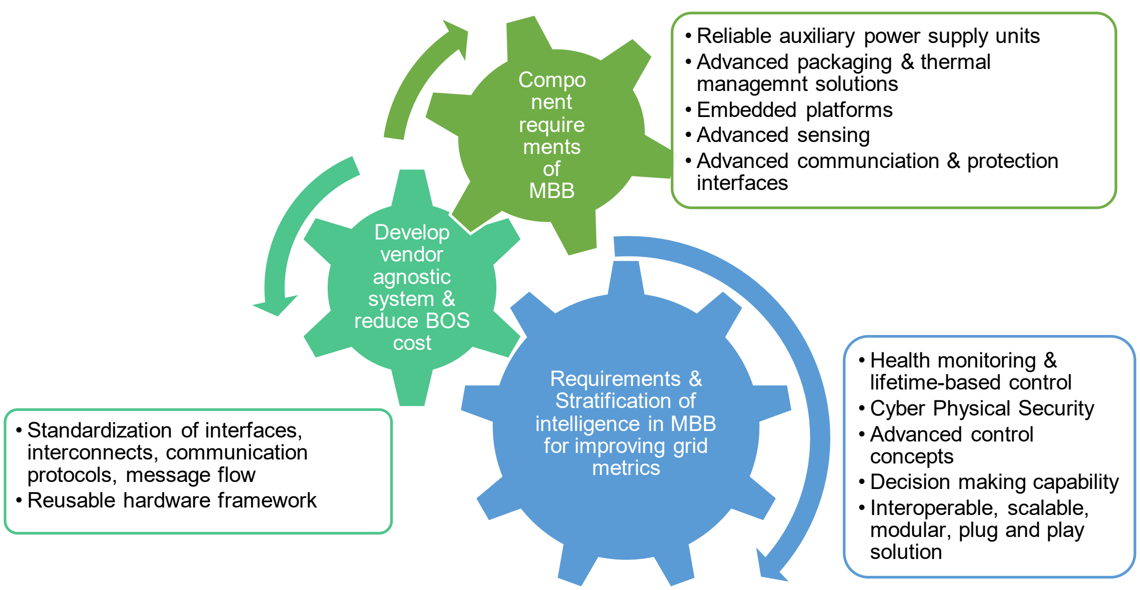


Figure 3: Vision for Development and Commercialization of Building Blocks

2.1 Vision 1: Development of Advanced Power Electronic Interfaces for the Grid

To enhance the grid metrics, the fundamental blocks must be designed to be robust and resilient and this calls for a holistic design with control, communication, protection, and intelligence. The holistic design approach is crucial to designing interoperable, scalable, and modular systems. Interoperability and scalability can be further enhanced with the inclusion of advanced features (listed in Table 2), including cyber-physical security, diagnostics, and advanced control algorithms. Together, these features will make the grid interface more reliable and resilient, i.e., minimize failures and downtimes and alleviate the impact of cyber threats. Such advanced building blocks can be used to demonstrate a microgrid with advanced functionalities. For example, after minor failure events the microgrid could continue to operate for extended periods of time in a "de-rated" mode using demand response or even automatic rolling load-shedding. On the other hand, after catastrophic failures, when a shutdown becomes necessary, it would be of great interest for the microgrid to have "limp home capability" to inform the critical loads of impending power outage and to set-up the system configuration and prepare all MBBs for the upcoming black start after the repair or removal of the failure cause. An example of such capability would be to retain a reserve level of energy storage and to keep the control and communication units running in all MBBs ("maintain the brain while the body recovers").

Table 2: MBB Features and Corresponding Grid Impact

MBB features	System Level Impact	Metrics
1. Interoperability	- Easy integration and reduction in BOS costs	Economics
2. Embedded intelligence and decision-making capability with a flexible scalable platform	- Improved voltage profile at the point of connection (POC) - De-rated/continuous operation during failure events	Reliability, Grid Support, Power Quality
3. Diagnostics	- Allows maintenance to be pre-planned - Prevents loss of the power-electronics-based resource from affecting the overall system - Increases lifetime	Reliability, Economics & Reduced Downtime
4. Embedded optimization & transactive functionality	-Cost benefits to the consumers -Market for ancillary services	Economics
5. Cyber-physical security	- Improved protection against cyber threats	Reliability, Resiliency, and Economics
6. Limp home capability	- Sustained operation in the event of failures	Reliability

2.2 Vision 2: Development of Advanced Subcomponents for the Advanced Grid Interfaces

With the vision to develop advanced power electronic interfaces for the grid, the R&D efforts should align to improve metrics such as power density, efficiency, and cost minimization. To this end, emphasis should also be on the development of advanced subcomponents required to realize features such as high bandwidth and noise immune sensing units, fault tolerant and reliable auxiliary power supply units, and embedded platforms for hosting advanced algorithms. R&D efforts are also required in the domain of packaging and thermal management to improve system power density and efficiency.

2.3 Vision – 3: Commercialization of Proposed MBB Technology

Standardization of the interfaces and interconnects will enable mass manufacturing and commercialization by reducing the balance of system costs. Standardization of the interfaces and interconnects will eventually lead to vendor agnostic systems and a streamlined supply chain. The end goal is to accelerate commercialization and adoption of such intelligent grid interfaces, nodes, or hubs to support modernization of the power grid with resultant improvement to reliability, resiliency, power quality, economic, efficiency, and security metrics.

As the product standards evolve, get adopted, and implemented by industry, it is essential that the development of standardization framework of MBB starts immediately. As MBB is a new technology, there are no adequate standards that will enable interoperability, modularity, scalability, and plug-and-play, and hence its commercialization will be highly dependent on early adoption of a standard reference framework. The situation is similar where inter-computer communications were 40 years ago: The Internet concept could not take off until the Open Systems Interconnection Reference Model (ISO/OSI) was adopted and TCP/IP standard accepted.

Deployment speed can be increased by establishing standardized technical and regulatory checklists for modular microgrid projects that use pre-qualified MBB hardware and software components.

3 Roadmap - MBB Technology Development

3.1 MBB Design, Implementation, and Testing

The building block can be defined as a common interface that allows for the interoperable integration of sources (generators) and sinks (loads) into a microgrid. The fundamental step in the roadmap is to design comprehensive specifications for every building block for microgrid applications. At the system level, the MBB performs the functions of energy management, communication, and control, as well as system-level optimization. The functions are shown in Figure 4. The next step in the roadmap is to design interfaces for every MBB. A particular MBB, depending upon its technical capability, may participate in a variety of microgrid services. Typically, each MBB can contribute to reliability services, resiliency services, and flexibility services depending upon its technical characteristics. A source MBB may have additional services such as black start, voltage support, frequency support apart from acting as a power source. A sink, if constituted with controllable load, may contribute to functions such as demand response, frequency stability, and voltage stability. Thus, the definition of services and interfaces constituted the first phase of the building block development roadmap.

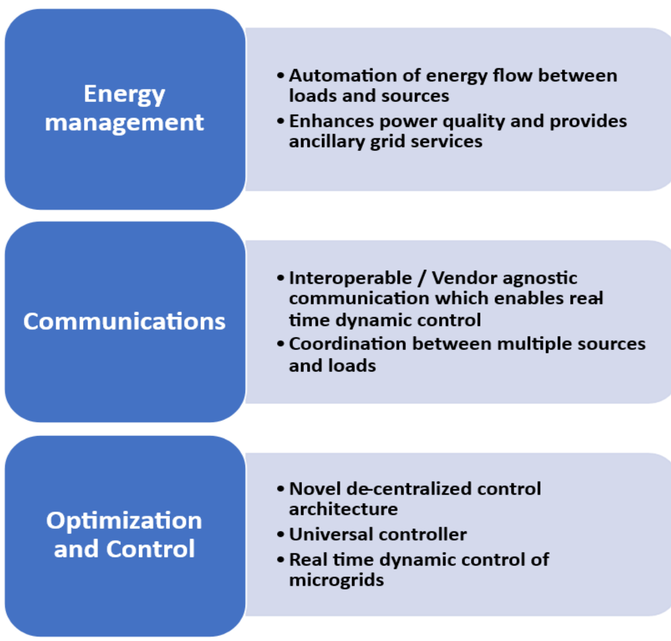


Figure 4: System Level Functions of an MBB

Once MBB interfaces and services from each MBB are defined the next roadmap phase is to develop global MG control architecture. Each MBB service contributes to a microgrid control function. These control functions can be black start, voltage stability, etc. Accordingly, the microgrid control architecture will be defined. The MBB will be required to meet certain performance requirements to achieve global microgrid control. A typical performance criterion could be how fast/reliable/stable each function needs to be. The MG control architecture design phase and the building block development phase are iterative in nature.

As MBB is a new technology, it is critical to demonstrate how a modularized MBB can help to simplify and reduce the cost for development, installation, and maintenance of a microgrid. One good example is to start with a basic utility/campus/community distribution system and use the MBB technology to develop the microgrid capability in the distribution system. This will demonstrate how the microgrid increases resilience and creates new opportunities such as ancillary services. It is likely that there are many smaller microgrids than large ones. Modular design will make a greater impact if many microgrids can show benefits from the MBB technology. Therefore, it could be the most appropriate for the program to deploy the first MBBs for smaller microgrid systems.

To support this effort, a comprehensive laboratory demonstration testbed will be established. This platform will be used to evaluate modular configurations, assess interoperability requirements, and refine standardized, compatible communication protocols with cyber-secure ports. The testbed will also provide an environment for pre-field assessments, ensuring that the MBB design meets operational, performance, and security needs before deployment in real-world systems.

The MBB testing approach will be executed in two stages: (1) unit-level testing to validate individual services and functions, and (2) integrated testing of multiple MBB units to assess coordinated operation and system-wide performance. The testbed shown in Figure 5 will serve as a low-voltage, at-scale evaluation platform capable of supporting distributed, programmable control for various microgrid MBB configurations testing with standardized interface control, communication modules.

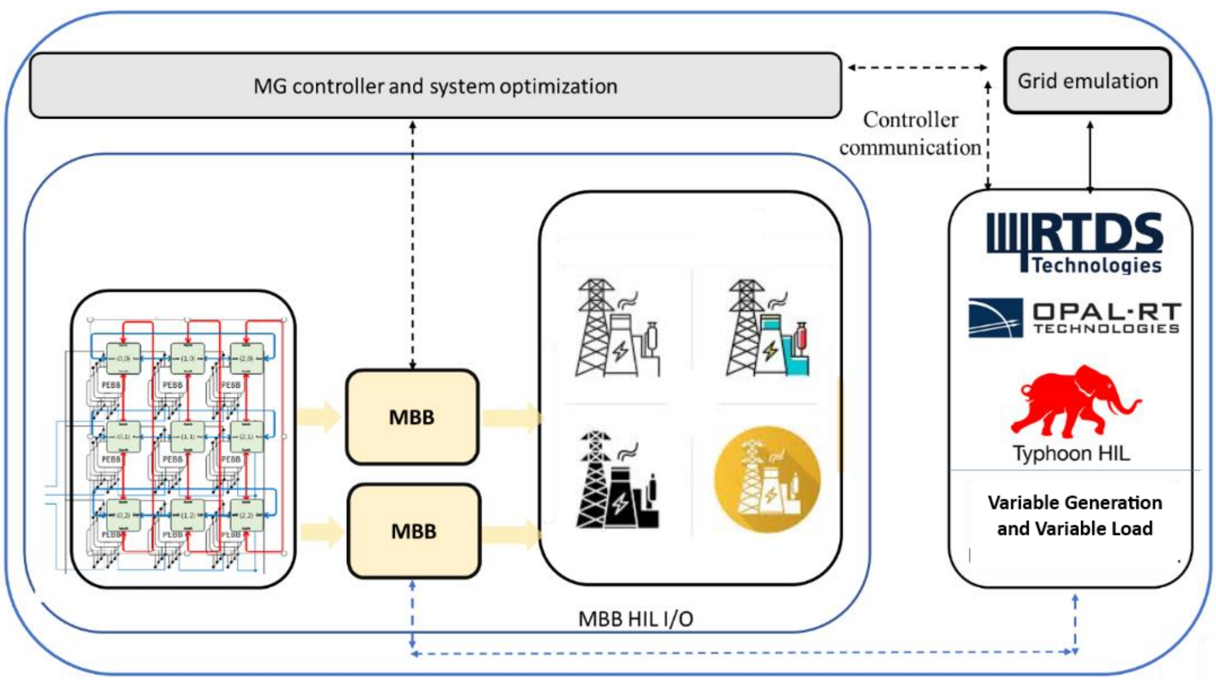


Figure 5: MBB Evaluation Platform Using Software and Hardware Platforms at DOE National Laboratories

A structured roadmap for MBB design, implementation, and validation was demonstrated in the work recently completed with key milestones shown in Table 1. The process begins with an analysis of generation and load profiles, incorporates functional requirements based on grid performance indicators, and progresses through architecture design, prototype development, and staged validation. The key objectives of this process are:

- Development of a universal MBB controller with ultra-fast local control to meet evolving grid codes.
- Implementation of a reprogrammable, plug-and-play control and communication architecture enabling seamless integration of diverse generators, energy storage systems, and critical loads.
- Advancement toward field deployment of a matured MBB solution that can cost-effectively enhance performance, reliability, and supply security for critical customers.

The final stage of the roadmap involves field validation, in collaboration with utilities, industry partners and research organization to demonstrate real-world applicability of MBB technology in microgrids. Successful deployment will mark a significant step toward standardized, scalable, and cyber-secure microgrid solutions which can be applied to a wide range of use cases including industrial manufacturing, mining and datacenters.

4 Cost-Benefits/Economics and Use Cases

4.1 Cost-Benefits and Economics

By introducing modularity and flexibility into existing microgrid architectures, the MBB concept can significantly contribute to (1) reducing uncertainty at the planning and operational stages, (2) standardizing the design of microgrids, (3) improving the exchange of flexibility services at the distribution level, (4) enabling innovative horizontal market approaches, (5) facilitating the integration of behind-the-meter distributed

generation assets, as well as (6) improving the reliability and resilience of power distribution networks. It is important to note that the MBB concept enables these capabilities; however, every MBB element does not have to encompass the full range of capabilities, as they may not be necessary for the operation and may increase the cost. With the MBB concept, certain functions may be coordinated by another MBB controller or device elsewhere in the system, e.g., a microgrid controller. These impacts translate into economic benefits at the microgrid level and to the electricity subsector.

4.1.1 Cost-Benefit Balance of Modularity

Standardizing communications, control, and power interfaces in Microgrid Building Blocks (MBBs) could raise a project's ICT infrastructure costs, but that portion is relatively small (about 2% of total cost for community/campus microgrids and up to 10 % for utility systems) (NREL 2018). However, this design approach cuts operational costs by:

- speeding fault detection, isolation, and repair, thereby reducing outage-related economic losses;
- lowering maintenance expenses;
- widening vendor choice and competition through interoperability.

During the project phase, standardization also simplifies design, shortens commissioning, and reduces investment risk. Over the long term, modularity makes it easier to renew or upgrade components, which facilitates asset management and upgrading strategy.

4.1.2 Value of Flexibility

The increasing penetration of variable generation assets and dynamic building load behavior increase netload uncertainties in microgrids. Uncertainty forces utilities to rely on conservative and costly planning and operation strategies such as over-investments in network capacity, active curtailment, or limiting the interconnection of non-dispatchable energy assets. Due to the control architecture, the MBB concept can guarantee robust netload limits in the interface between blocks (e.g., via control setpoints), which significantly contributes to mitigating of the impact of uncertainty. Additionally, MBBs give microgrids the potential to avoid the propagation of uncertainty across different areas of the utility network and to the bulk power system. MBBs can locally address the impact of uncertainty, leading to decreased operational and planning costs that derive from unmanaged uncertainty. To unlock these uncertainty management capabilities of MBBs, innovative supervisory control functions are required. To capture the value of MBB in cost reduction, existing microgrid/distribution grid optimal capacity planning, economic operation, and valuation tools should be updated to model the added flexibility provided by the MBB architecture.

4.1.3 Value of Resilience

Traditional grid investment strategies, such as line hardening and topology redundancy establishment, are expensive forms of guaranteeing security and continuity of electricity supply to the consumers. Consequently, the flexibility introduced by the MBB concept can be a cost-effective form of maintaining overall network reliability and resilience, minimizing the microgrid loss of load during routine equipment failures, mitigating the impacts of High-Impact Low-Frequency (HILF) events, and protecting critical infrastructures. To determine the additional reliability and resilience value of MBBs, it is important to evaluate the impacts of different block configurations on outage mitigations, namely in 4 dimensions: (1) reducing the magnitude of disruption, (2) extending duration of resistance, (3) reducing duration of disruption, and (4) reducing duration of recovery. Probabilistic simulation methods across various microgrid topologies, compatible with MBB architecture, are needed to capture costs, values, and key reliability and resilience performance of microgrids.

4.1.4 Transactive Energy Management Value

Transactive energy management has emerged as a form of coordinating the multiple agents in power systems (prosumers, aggregators, retailers) while considering their particularities, priorities, interests, and autonomy. The idea is to optimize the allocation of resources (e.g., generation, controllable devices, and loads) by enabling actors to interact with each other and exchange information about consumption, generation, constraints, and preferences until an equilibrium solution is reached. When it comes to enabling these transactive solutions from a grid operation perspective, the characteristics of MBB architecture can be decisive. In fact, due to its decentralized nature, MBBs can simplify the integration of these horizontal markets and services, allowing utilities and microgrid operators to guarantee operational limits and reduce market constraints, favoring clearing mechanisms and decreasing costs. To achieve this, expanding the MBB concept to economic and market standardization aspects is important, such as development of price elasticity functions that can capture the response of the individual blocks to variations in energy prices. To show the value of MBB as an enabler of transactive energy markets, the research effort needs to include the development and demonstration of realistic cases, which would measure the economic benefits of MBB-based transactive control in comparison with current microgrid hierarchical control approaches.

4.2 Use Cases of MBB

4.2.1 Microgrid as a Resiliency Source

Virginia Tech Electric Service (VTES) is a 60 MW distribution system (owned and operated by Virginia Tech), with power served from Appalachian Power (part of American Electric Power). To improve the system's resilience, large-scale distributed generation facilities and energy storage will be developed and deployed near the campus town of Blacksburg, VA. As shown in Figure 6, the proposed MBB serves as a building block to provide functions of power conversion, communications, and control for the microgrid. When the AEP system becomes unavailable due to extreme events, the VT microgrid can operate in a resiliency mode to serve the critical load on campus and in Blacksburg. The microgrid control and communications will be built upon the existing VTES grid control and communication facilities. New sensors, communication, and control components and systems will be developed to complete the microgrid design. A pilot study on MBB has been conducted at Virginia Tech in a project sponsored by DOE Office of Electricity and Pacific Northwest National Laboratory. The MBB at the PCC integrates the primary functions of power conversion, communications, and control for the microgrid. By modeling and simulation, the power conversion capability of the MBB demonstrates successful operation under islanding, black start, and unbalanced loading conditions. Communication and control functions of the MBB maintain the microgrid stability under the operational conditions of real/reactive power dispatch, frequency/voltage regulation, and stabilization under large disturbances.

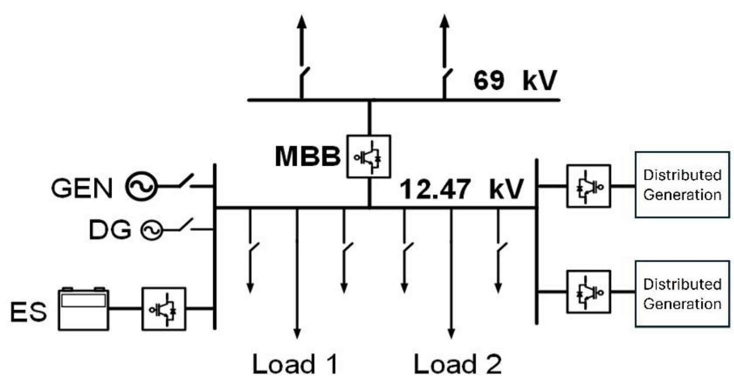


Figure 6: Illustration of MBB for Virginia Tech Electric Service Grid

4.2.2 MBB-based Microgrid in Alaska

Alaska has several rural microgrid power systems with capacities ranging from 30 kW to multi-MW levels. The generation and load mix are seasonal and variable. Several of these microgrids operate as isolated rural power systems with low inertia, operate under harsh weather conditions, and pose control and stability challenges. MBB-based architecture offers several advantages for maintainability, modularity, flexibility, and resiliency. This approach reduces the risk and cost of field deployment, operation, and maintenance by standardized building blocks and combining several subsystem controllers into a universal controller. Leveraging existing work and results on microgrid control design from DOE-funded project in Cordova, AK, an MBB-based microgrid design can be pursued. To reduce the risks of MBB-based development while quantifying its efficacy/value, the performance assessment of MBB will be done using emulation and hardware testbed. The MBB architecture can be used to design multiple potential locations with different sink & source MBBs, including a universal controller in EMT simulation, and controls prototyped in a hardware testbed environment. The actual field data from Alaska can be used to emulate and test various MBB control architectures.

4.2.3 MBB: A Critical Enabler for Resilient Datacenters:

The MBB design should include integration points for emerging generation assets, such as Small Modular Reactors (SMRs) to ensure interoperability and standardized control within the microgrid building block framework. MBB technologies must be designed to support emerging critical loads, such as data centers, that demand high reliability, scalability, and secure integration. The MBB technology has the potential to serve as a viable interfacing solution for datacenters, enabling them to ride through uncertain and dynamic grid events that could otherwise disrupt operational continuity and planning schedules. Its ability to support both normal and abnormal utility grid conditions enhances the resilience and maintainability of datacenter operations. Additionally, the controlled soft-start and shutdown capabilities of MBB can minimize transient impacts on the utility grid, preventing further deterioration during grid disturbances. Its modular architecture and adaptive control capabilities allow datacenters to seamlessly interface with diverse and variable energy sources, manage fluctuations in supply and demand, and ensure high reliability without compromising performance or uptime.

4.2.4 MBB Applications to Mining and Critical Material Extraction

To accelerate U.S. rare-earth production, remote mining sites need reliable, fast-deployable electrification without bespoke engineering. Standardized MBB delivers a vendor-agnostic platform that integrates on-site generation (gas, energy storage systems, SMR) and large variable mining loads under modular compatible layer with defined physical, control, and communications interfaces. MBB controllers interoperate with existing gensets/PLCs via Standardized protocols (Modbus, MQTT, IEC-61850, DNP3) enabling plug-and-play integration and preserving primary device controls. The MBB power conversion system provides seamless grid-connected/islanded transitions, black-start, and selective shedding, while embedded control profiles mitigate sags, flicker, harmonics, and motor-start inrush. This provides higher reliability and resilience during grid events, compressed deployment timelines, and reduced balance-of-system costs. This scalable, modular MBB based microgrids boost the electrification of mining loads, de-risks operations in remote last-mile locations, and gives utilities and operators a consistent pathway to expand capacity while improving power quality, safety, and cost control. It delivers a scalable path to policy-aligned, 100% electrification that supports national supply-chain goals while giving utilities and mining customers a durable, replicable solution.

4.2.5 MBB: Scalable Deployment Templates

To accelerate practical deployment, future work should prioritize the development of pilot-ready MBB configurations designed to a range of microgrid scales, including less than 1 MW, 1–5 MW, and 5–20 MW. Each configuration should provide estimated costs, deployment timelines, and modular implementation steps to support end users through system design and integration. These reference models would help stakeholders evaluate feasibility, reduce planning uncertainty, and demonstrate how MBBs can be adapted across diverse project sizes and deployment contexts.

5 Related Enabling Technologies

MBB concepts leverage many different technologies, from those related to the underlying power electronics to simulation and optimization software to deploy and operate MBB-based designs. This section will provide a high-level discussion of technologies associated with MBB, facilitating the identification of mutually beneficial research and development needs.

Technologies related to power electronics will clearly play a key role in MBB deployment and utilization. As the different building-block components are added or removed from a microgrid, the electrical interconnections and overall energy capabilities will be major considerations for how blocks are reconfigured. Such devices must be able to interface through some common, preferably vendor-agnostic, connection or framework to provide their individual capabilities to the larger microgrid. Technologies that provide electrical protection during these reconfigurations will also enable the MBB concept. Determination on the smallest reasonable “build block unit” is also key here, allowing the building block concept to extend into individual distributed energy supply and demand assets and devices, not just at an interconnection bus level. Concepts such as PEBB and SPSS frameworks explore many of these aspects and will be heavily leveraged.

While the connection of the power electronic and underlying power devices is a key component of MBBs, the communication and control of the building blocks and their aggregate are equally important. Mesh-based and ad-hoc network connection technologies will enable easier integration of various building blocks, especially through a common communication interface. Existing technologies, such as WiFi, WiMAX, and cellular networks, will be key to enabling the exchange of information on the interconnected microgrid building blocks.

With the underlying power electronic capabilities and communications to exchange data, various forms of standard and secured controls will be needed to properly coordinate and operate the building blocks for the microgrid. Underlying technology concepts, such as swarm or flock control approaches, may be needed for MBB components to properly interact and provide a larger capability in the individual microgrid. On a higher level, microgrid controls and hierarchical control technologies and schemes will be needed to coordinate the various devices. Controls that adjust to new capabilities being added will need to be expanded or developed, especially for operational control.

The design and operation of building block-based microgrid systems will require simulation and modeling packages. Coordination and evaluation between different model fidelities of the building blocks (e.g., electromagnetic vs. electromechanical time scales) will leverage co-simulation technologies, which are covered in detail in the Topic Area #2 strategy document. For real-time operations, technology to execute the analysis within operational time constraints will be needed, which may include parallel and cloud computing approaches.

In the past several years, optimization and control technologies for microgrids to operate in a resiliency mode without support from the utility sources have been developed, e.g., (Gao et al. 2016)(Xu et al. 2018). These methods are used to optimize the utilization of available generation resources to sustain service to critical load during an extended outage of the utility system. Methods for control and dynamics are also available to steer the microgrid back to nominal values following frequency and voltage deviations due to small or large disturbances (Lee et al. 2020).

It is recommended to develop a technical deployment guide for MBB implementation, providing specifications, interoperability requirements, and interconnection procedures to support utilities and developers in rapid adoption.

6 Summary and Conclusion – R&D Recommendations for the Next 5 Years

Building on the outcomes and lessons learned from the initial MBB concept validation project, future efforts should prioritize transitioning the MBB system from controlled laboratory validation to field deployment in operational, utility-scale environments. This progression will involve expanding the MBB framework to support larger and more diverse microgrid topologies, while ensuring robust protection coordination and high-performance communication with the MBB controller

Further research should include comparative evaluations of MBB capabilities against existing commercial microgrid controllers to quantify performance advantages and identify potential integration gaps and it's application areas in changing grid configurations around load centers. Equally important will be the systematic analysis of deployment challenges at utility scale, supported by the collection of critical operational data to inform industry best practices and accelerate widespread adoption across diverse geographic service areas and isolated communities For the pilot-scale deployment, the National Standard Practice Manual (NSPM) has been developed as the basis for cost-benefit analysis (CBA). Using such a framework, a standardized, replicable CBA can be constructed that captures traditional capital cost impacts and quantifies the monetary value of qualitative operational gains, especially the enhanced reliability and resilience delivered by the MBB functions support the faster load growth including datacenters, industrial manufacturing and rare earth minerals mining.

Commercialization will be a pivotal step in realizing the full potential of MBB technology. Once R&D and field demonstrations reach a mature stage, targeted engagement with manufacturers and potential spin-off ventures will be essential for implementation and technology transfer. In alignment with DOE's long-term objectives, next-generation MBB platforms should integrate AI/ML capabilities to leverage big data, enhance decision-making, and ensure seamless interoperability—both within individual microgrids and across interconnected systems.

Based on this vision and roadmap, detailed recommendations for future R&D are compiled in Table 3.

Table 3: R&D Recommendations

No.	Title	Priority	Timeline	Key Task	Expected Impact
R1	MBB-Based Microgrid Implementation & Field Test with all features of MBB	High	Short-term (1-3 yrs)	Deploy and test a full MBB microgrid on a distribution feeder under grid-connected and resiliency modes for critical loads.	Demonstrates operational and cost benefits; paves way for large-scale adoption by utilities and communities.
R2	Development of MBB standardized ratings and interoperable interfaces using Low Voltage at-Scale Validation Platform	High	Short-term (1–3 yrs)	Develop standardized control and communication of MBB for interoperability and modularity through low-voltage Testbeds with help of CHIL/HIL and MW scale distributed energy supply and demand assets	High-fidelity environment to verify interoperability, modularity, flexibility, resilience, lowering engineering cost.
R3	Development of Protection and Controls for Transient Performance Enhancement of MBBs	High	Short-term (1–3 yrs)	Design and implement advanced protection schemes and coordinated control strategies for MBB during fault, switching, and large disturbance conditions. Integrate adaptive protection and dynamic reconfiguration control capabilities	Provides scalable, modular MBB systems capable of maintaining stability during faults and disturbances.
R4	MBB Design and Validation to Demonstrate MBB Features in Emulated Real-World Environment	High	Short-term (1-3 yrs)	Use the R1 and R2 platforms to develop advanced controls and validate stackable MBB features with tightly networked nodes.	Accelerates innovation via disruptive at-scale HIL testing rather than slow analytic-only iterations.
R5	Development of Building Block Architectural Approaches	Medium	Medium-term (3–5 yrs)	Define and evaluate centralized vs. distributed MBB architectures with associated power, comms, and control.	Provides modular, reliable, cost-effective design templates for diverse microgrid needs.
R6	Modular, Scalable Integrated Software Platform with Real-Time Control Capabilities	Medium	Medium-term (3–5 yrs)	Build a real-time software stack for data acquisition, command delivery, and inter-node sharing.	Enhances software reliability, maintenance, and scalability for wide deployment.
R7	Modular, Scalable Design and Implementation of MBB Communication and Control Systems	Medium	Short-term (1–3 yrs)	Develop cost-effective, cyber-secure comms and control ensuring stability across operating conditions in different utility settings.	Improves performance and lowers O&M costs of MBB microgrids.
R8	Smart Reconfigurable System for Any Microgrid Systems	Medium	Long-term (5 yrs)	Develop adaptive reconfiguration capabilities that apply to power conversion, communication, and control systems for varying generation/load scenarios in MBB-based microgrids.	Delivers heightened flexibility and performance as microgrid conditions evolve for critical loads.
R9	Demonstration of Market Participation in a Distribution System Environment	Medium	Long-term (5yrs)	Extend MBB functions to wholesale/retail markets; optimize energy & ancillary-service bids.	Generates new revenue streams via transactive energy and optimized trading.

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