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Net-zero Microgrid Program Report:

Microrred de la Montaña Feasibility Study

July 2022

Executive Summary [Extended]

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The Net-Zero Microgrid Program provides cross-cutting research to accelerate the use of renewable and zero-carbon generation in microgrids.

Idaho National Laboratory

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ACKNOWLEDGMENT

This feasibility study was prepared from the results of the research and design (R&D) project to develop a community microgrid application and hydropower component for the Net-zero Microgrid Platform under the FY 2023 Department of Energy Office of Electricity (DOE-OE) microgrid Program. The data for the community microgrid application and hydro component were conveniently provided by the Cooperativa Hidroeléctrica de la Montaña – cooperatively and pro-actively. A feasibility study for the community microgrid – the Microrred de la Montaña – was a logical and value-add extension of the R&D project resulting in a solid technical and economic rationale and justification for achieving the vision of the Cooperativa Hidroeléctrica de la Montaña.

The authors of this feasibility study and the Cooperativa Hidroeléctrica de la Montaña acknowledge the support and leadership of Dan Ton, Program Manager DOE-OE Microgrid Program.

Cooperativa Hidroelectrica de la Montaña

XENDEE

EXECUTIVE SUMMARY

INTRODUCTION

This feasibility study provides the technical and economic rationale for the Microrred de la Montaña as a viable solution for supplying reliable and resilient electricity to an underserved region in Puerto Rico – a region that is the first to be disconnected from the grid and the last to be restored, enduring months long outages. It begins the process of the development of the microgrid through conceptual design, engineering, detailed electrical design, implementation, and operation.

The Microrred de la Montaña is organized under the governance of the Cooperativa Hidroeléctrica de la Montaña (Cooperativa) which has legal status as a cooperative and power provider under the laws of Puerto Rico. The members are the municipalities of Adjuntas, Jayuya, Lares and Utuado with a combined population of 90,000. These municipalities are in central Puerto Rico – a mountainous region that is extremely vulnerable to weather events and excessive, long-duration power outages and are among the poorest and most disadvantaged regions in Puerto Rico. Funding from external sources is necessary to acquire the resources for a resilient power delivery system. Regulatory support is necessary to establish operational relationships with the incumbent power providers.

The Microrred de la Montaña is envisioned as a resilient microgrid that manages distributed energy resources – local solar, storage, and hydroelectricity over an upgraded distribution network within the boundaries of four municipalities.

This feasibility study provides the results of an extensive techno-economic analysis to form a sound basis for decision-making by community leaders, their constituents, funding and investment agencies, and regulators to realize the benefits that are achievable by fully implementing the design and planning recommended for the Microrred de la Montaña.

MICROGRID GOALS AND BENEFITS

Today, customers in the municipalities within the microgrid's boundary receive power from the central generation owned by the Puerto Rico Energy Power Authority (PREPA) and delivered via the transmission/distribution networks managed by LUMA Energy. Oddly enough, hydroelectric plants existing within the boundary of the microgrid service area supply power to the transmission network for central dispatch to other regions in Puerto Rico, while customers in the Cooperativa are neglected

The Cooperativa recognizes that it must begin to install local solar and storage today to provide power to certain critical loads, offering a modicum of resiliency to the local communities. This work has already started with the installation of a small microgrid and will continue as more funding becomes available for the Cooperativa. Thus, it is at this juncture that a feasibility study is warranted and of great value at this initial stage of forming the microgrid.

The feasibility study considers the collective generation capacity as resources for a microgrid and proceeds to analyze their expanded deployment in the context of a fully developed microgrid. Without being configured as a microgrid, these resources are only backup power for a limited period of time. A microgrid requires dispatchable generation in order to maintain stability when separated ("island") from the grid. Within the boundaries of the Cooperativa's service area are the hydroelectric plants served by the Caonillas and Dos Bocas reservoirs that are an ideal source of dispatchable power.

The feasibility study covers the main elements for the design and planning for the Microrred de la Montaña. It progresses through three stages of development that coincide with the expected acquisition of resources and available funding: 1) solar/storage at customer sites and substations – both connected to the existing distribution system (LUMA Energy) with power supply from the central generation (PREPA); 2) hydropower generation; and 3) optimal planning and dispatch – microgrid – integration of all resources in a fully operational microgrid. These three stages – identified by the project plan of the Cooperativa – are described briefly below.

Project Plan Stages – Cooperativa Hidroeléctrica de la Montaña

1. Resiliencia Energética Fotovoltaica Comunitaria (ReEnFoCo) – installation of photovoltaic panels with storage to keep key resources for each community powered. This effort is focused around providing energy for specific resources the community needs during outages, including food, medical, water, and emergency services.
2. Hidroenergia Renace (Hydroenergy Reborn) – refurbishment and upgrade of hydroelectric resources at Caonillas and Dos Bocas reservoirs. This includes improved storage capacity for the reservoirs and improved reliability and capacity of the turbines and generators. Peak power production will be increased from a current 6 MW to 50 MW peak capacity. Operational control of the two hydroelectric plants is a prerequisite. The project includes direct electrical connectivity with the distribution networks in the four municipalities by way of a new 38 kV transmission line.
3. The Microrred de la Montaña – integration and management of the resources of Hidroenergia Renace and ReEnFoCo as a single controllable entity – a microgrid. This will require an energy management and control system (including supporting telecommunications).

MICRORRED DE LA MONTAÑA

Figure ES-1 shows the nodes for hydropower generation, local solar and storage resources, and connectivity of the four municipalities (new sub-transmission line to the hydro facility and existing distribution network). Note that the existing connection to the transmission network in Puerto Rico will be retained.

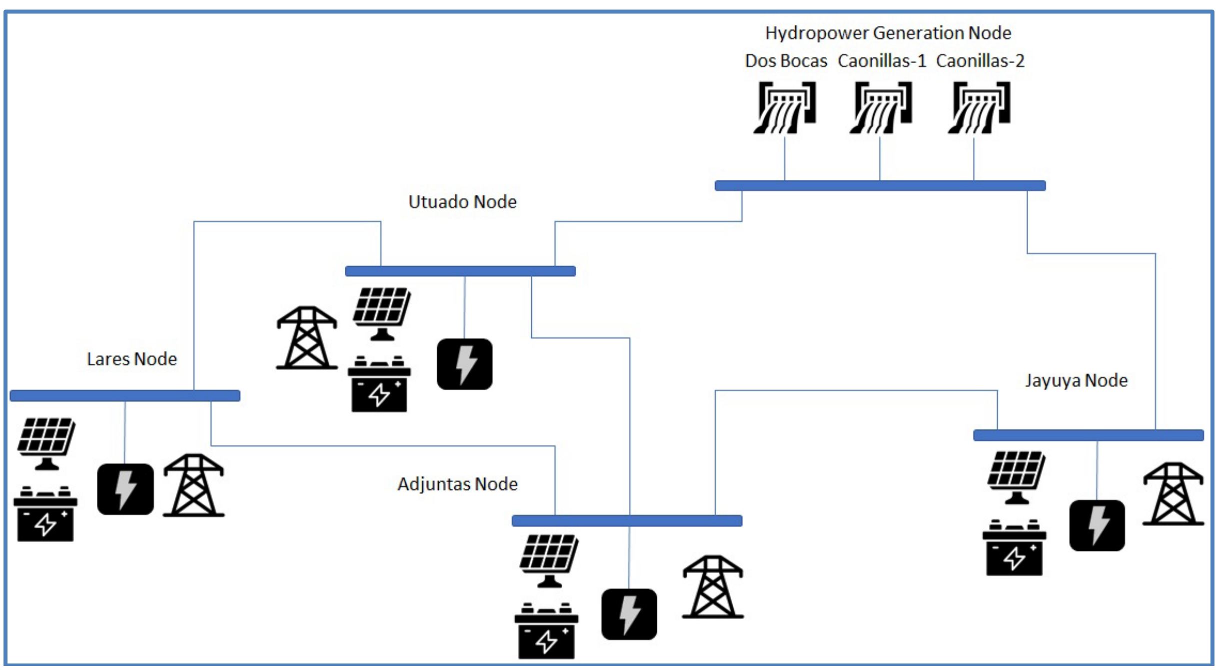

Figure ES-1. Microrred de la Montaña – Nodal Diagram

SITE ASSESSMENTS AND CONFIGURATION
The geographic view of the Microrred de la Montaña provides insight into the sophistication and scale of this project as four different communities are considered for microgrid design together with transmission lines connecting to three different hydroelectric plants in the region. The feasibility study includes geographical information system (GIS) maps of the Microrred de la Montaña project, including the Caonillas-1 and Caonillas-2 hydroelectric plants with switchgear and substations at Dos Bocas each of the four municipalities. Figure ES-2 shows the overall view of the individual communities and the hydroelectric plants.

Figure ES-2. The Microrred de la Montaña - GIS View

APPROACH – MODELING AND ANALYSIS
The approach to modeling and analysis followed the three stages of development for the microgrid. The results yielded the optimal technical and economic design for achieving a resilient electricity supply with proven technology that is achievable with reasonable funding from sources available in Puerto Rico from the U.S. Government and regulatory approvals in Puerto Rico.

This feasibility study includes an analysis of the costs and benefits of the plan and defines the logical next steps in designing the system. The analysis requires a high fidelity understanding of the municipalities' electric needs, along with solar and hydroelectric resources to determine the amount of storage that produces a resilient system while achieving an optimal financial outcome for the Cooperativa.

Sustaining power delivery for all customers (the entire load within the boundary of the microgrid) for long duration outages caused by extreme weather events beyond a few days requires large investments in local generation and storage is prohibitive costs. The practical solution is to prioritize loads within the microgrid to ensure sustainable power to critical infrastructure (lifeline systems) to be supplied by available energy resources.

The modeling considers solar, storage, and hydroelectric generation plants. Various optimization scenarios are created revolving around these DER technologies and resiliency factors.

Solar/Storage

The approach began with a scenario for solar and storage at customer sites and substations to provide resilient power to the loads in the four municipalities to sustain a 3-day outage and optimizing the available resources. The result was that the amount of solar/storage that could be realistically installed was infeasible – requiring greater than 100 MW over unfavorable terrain (mountainous).

This led to a scenario that determined the practical amount of resources that could be installed (e.g., the surface area available for solar installation – rooftops and open areas) and the financial resources available for investment. The analysis yielded a level of power available for the microgrid from which a power allocation could be assigned for each municipality. Situations were identified where the critical load power assignment could be determined based on the available solar/storage.

The power assignments to the municipalities were prioritized to serve critical loads for a given outage duration. The needed amount of storage was calculated for a continuous 365 days/24 hour duration outage. The 365/24 criteria is a reasonable requirement given realistic expectations of substantial major damage from tropical storms that frequently disconnect the mountain regions from the transmission networks that deliver power from the central power plants operated by PREPA for weeks or months. The solar/storage scenario was analyzed in relationship to a base case of power supply today by PREPA and LUMA Energy over long transmission lines that are highly vulnerable to weather events.

Hydropower Generation

The inclusion of hydropower as dispatchable generation is a distinguishing feature of the Microgrid and a vital component of the Net-zero Microgrid Program.

The microgrid requires dispatchable generation in order to be self-sufficient, island, and provide full resiliency to the community. This is available directly from hydropower resources within its boundaries – Lago Caonillas and Lago Dos Bocas. The hydroelectric generation plants for this feasibility study include Caonillas-1, Caonillas-2 and Dos Bocas. These plants are located in the Caonillas-Dos Bocas hydroelectric system. Power is planned to be delivered directly to substations within the microgrid by way of new 38 kV lines. This feasibility study provides the basis for sizing of conductors, transformers, breakers, and switchgear for this new infrastructure.

OPTIMAL PLANNING AND DISPATCH – MICROGRID

The planning and dispatch analysis was conducted using the techno-economic decision-making platform built by XENDEE.

The energy flows and the DER technologies that were modeled in the XENDEE optimization engine included the choices for energy purchase and sales, on-site energy sources comprising of various DER technologies and fuels, local storage options, and end-use equipment comprising of essential demand types specific to the Microrred de la Montaña project.

Constraints associated with power quality, climate, reliability, energy storage operation, regulatory functions, financial functions, operation limits, and energy balance specific to the boundaries of the Microrred de la Montaña were built into the model.

The technology for solar photovoltaics and battery energy storage currently being installed in the Microrred de la Montaña was used in the modeling.

Determining the physical and operational characteristics specific to the hydropower generation facilities available to the Microrred de la Montaña was a critical part of the overall analysis. This was done by integrating HydroGenerate, a tool developed by INL to estimate hydropower generation, and integrating it into the NZM. A method of calculating the power production versus historical water flow into the reservoirs using the specifications of the height of water was implemented and provided as an input into the model as power curves.

DATA GATHERING AND OPTIMIZATION STRATEGY

The data collection and results of the modeling and analysis are presented in detail in eleven tables and 83 figures of the feasibility study. Input data was collected for all loads, generation profiles were normalized for the solar PV and hydropower generation units, and power flow parameters were calculated for the transmission lines and substations. The optimization strategy revolved around conducting an analysis of power budgets for municipalities defined at two different resiliency levels. Alternative scenarios were created to evaluate the available input data, resiliency factors, and assumptions on load data.

Load Data

Data related to the electrical consumption of each community was obtained from LUMA Energy for FY2021. This data were obtained using smart meters at the substations and were considered as the aggregated demand for each community. There were some gaps in the data which necessitated preprocessing; missing load data was replaced by the values in each substation from the same hours of the same day type of the week or weekend. The load peaks inside each community were preserved in the pre-processing step.

Data for Annual Energy [GWh] and Annual Peak [MW] suitable as input to the model by substation was obtained for each of the four municipalities. The total annual energy of aggregated communities is approximately 212 GWh and the annual peak demand of aggregated communities is approximately 34 MW. Full year time-series load profiles were developed on hourly basis for each of the community substations. Together with these annual load profiles, daily load profiles for each community were analyzed.

The load profiles used in the analysis were verified from the templates provided by PREPA for residential, commercial and industrial loads which were considered for the design of the microgrid for each community.

Variations in the load profiles gave additional information to help define the requirements for control systems for microgrid dynamic control and energy management system specifications to efficiently manage energy, customer accounts, and exchanges with the serving utilities.

Solar PV Data

The monthly solar PV performance in terms of AC output normalized by the rated DC capacity was calculated by XENDEE at the location of each community. The solar PV technology costs and technical lifetime are based on the Puerto Rico distributed energy resource integration study. The solar PV inverter costs are indirectly considered within these costs. For solar PV, this feasibility study considers the investment costs of 1,860 $/kW, the O&M costs of 10 $/kW/year, and a lifetime of 25 years.

Battery Energy Storage System Data

For this feasibility study, a 4 hour duration battery energy storage system is considered. The technology costs of battery energy system are based on IRENA’s electricity storage costs. For the battery energy storage system, this feasibility study considers the investment costs of 563 $/kWh, and a lifetime of 15 years. The inverter costs indirectly are considered within these costs. The O&M costs are considered to be zero.

Hydroelectric Generation Data

The Caonillas-Dos Bocas hydroelectric system consists of two major reservoirs i.e., Caonillas reservoir with the Caonillas-1 and Caonillas-2 hydroelectric plants (Caonillas-2 is the upstream development); and Dos Bocas reservoir with the Dos Bocas hydroelectric plant (Dos Bocas is the end of the development). INL's hydropower profile generation model i.e., HydroGenerate was used to get the time-series profiles of each plant depending upon their technical characteristics.

The Caonillas-1 plant has two units having 10 MW capacity each. The annual net generation of Caonillas-1 obtained by the HydroGenerate using the United States Geological Survey (USGS) data is 50,636 MWh at 20 MW rated capacity. Caonillas-2 plant was flooded during Hurricane Georges in 1998 and has not been operational since. Caonillas-2 has one unit having 4 MW capacity, and currently the capacity is 0 MW after the damage. PREPA conducted a study to decrease the potential capacity to 1 MW. This feasibility study considers 4 MW capacity rather than PREPA's recommended 1 MW because of maximizing the output of hydropower to the communities. The annual net generation of Caonillas-2 through the obtained by HydroGenerate using USGS data is 10,127 MWh at 4 MW rated capacity.

Dos Bocas hydropower plant has three units each having a capacity of 5 MW. The average net annual generation estimated by PREPA for Dos Bocas is around 30,650 MWh at rated capacity of 15 MW. With the water flow data from USGS and the technical characteristics for Dos Bocas, INL's model was able to calculate the time-series power potential with exactly the same annual net generation as PREPA's estimation. These calculated power potential profiles of each hydropower plant were normalized by their rated capacities and then used in the XENDEE optimization engine. The total technology installed costs or CAPEX for hydropower plants in central America region are reported to be $3,462/kW. The OPEX are reported to be 2% of total CAPEX. These costs are based on the IRENA Renewable Energy Cost Database of 2020.

Power Flow Data

To consider power flow in XENDEE optimization engine, the data for transmission lines from the hydropower plants to the community stations was obtained from LUMA Energy. The illustrative one-line diagram, Figure ES-1, was used to design the transmission lines and substations in XENDEE optimization engine. There are two substations at both Jayuya and Lares municipalities and only one substation at both Adjuntas and Utuado municipalities. There are new 38 kV transmission lines connecting the community substations to the hydropower plants. The Dos Bocas switchgear is the central point for all the power flow from the hydropower plants. All the 38 kV transmission line are assumed to consider a resistance of 0.054 Ω/km, a reactance of 0.0655 Ω/km, and ampacity of 1520 amperes. The transformers at the substations in each community are rated as follows: Adjuntas at 10.5 MVA, Jayuya-1 at 12.69 MVA, and Jayuya-2 at 10 MVA, Lares-2 at 7.2 MVA, and Utuado at 7.5 MVA.

Utility Data

The utility services are managed by LUMA Energy in the region. The utility tariff imposed by Puerto Rico Energy Bureau for each community is the same and, at the time of the study, was flat at $0.285/kWh for purchased/sold residential utility electricity. The electric rate has since increased to $0.334/kWh (July 2022), which further improves the value of the Microrred de la Montaña project to these communities. Hourly marginal emissions are considered in the feasibility study to take into account the carbon emissions emitted while purchasing the electricity from the utility. Natural gas-fired power plants generated 44% of the island's total electricity, petroleum 37%, coal 17%, and renewables 3% (FY2021). By pro-rating the CO2 emissions by the national average for the fuel source, the total marginal CO2 emissions are 1.5676 pounds CO2/kWh or 0.711 metric tons CO2 emissions /MWh. Therefore, 0.711 metric tons CO2 emissions /MWh, which is the value used in this study.

Financial assumptions

A 6% interest rate and 20 years as maximum payback time of the project have been considered in this study. No federal tax rate has been considered. Also, this study does not consider any incentives on technologies or tax credits.

RESILIENCY

The communities in Puerto Rico including the communities of Adjuntas, Jayuya, Lares, and Utuado have struggled in the past to deal with the reliability, and resiliency or electric power outage from PREPA. Due to the geographic nature of these communities, a self-resilient power system is critical need of the people of these areas regardless of their customer class of residential, commercial or industrial. Two different resiliency levels are considered for this study which are described below.

Resiliency for Critical Infrastructure

The first resiliency level is termed as "resiliency for critical infrastructure", alternatively referred to as "resiliency with critical load serving". The resiliency for critical infrastructure is based on a critical load in each community which must be satisfied 24 hours for 365 days, i.e., all year in an islanded situation where there is no supply from utility, and hydropower plants. Only solar PV, and battery energy storage system are allowed to provide to this critical load which are identified by XENDEE optimization engine through power budget analysis. This resiliency with critical load serving is especially important for a community microgrid design of the Microrred de la Montaña project since the region is always at risk of becoming isolated due to hurricanes resulting in utility outages of months, possible damages to the transmission network, and flooding of substations.

Resiliency for all Customers

After identifying the resiliency with critical load serving, it is also important to consider additional layer of resiliency which provides optimal solution in connected communities using full original load data. The resiliency for all customers or the full resiliency considers the communities connected with each other and an outage period (one day or three days) where these communities are isolated from the utility. This resiliency level still encapsulates the critical loads, hence the critical resiliency in connected communities.

Optimization Scenarios

The optimization scenarios define the optimization strategy for the Microrred de la Montaña project. XENDEE optimization engine uses the data and assumptions provided above and produce an output that provides the cost optimized mix of DER technologies in terms of their capacities, their optimized operation dispatch, the cost savings, carbon emission savings, cash flow analysis, detailed energy balance among sources and load, and power flow analysis. The optimization scenarios of this feasibility study include all the necessary factors of the reliable and resilient microgrid solution for the Microrred de la Montaña project taking into the resiliency for critical infrastructure as well as the resiliency for all customers. A base case scenario was created for the solar/storage scenario using data provided by PREPA/LUMA Energy. The base case scenario only considers the utility electricity from PREPA/LUMA Energy to supply the consumption of each community. All investment optimization scenarios are compared with the base case scenario.

TECHNO-ECONOMIC RESULTS BY SCENARIO

The results of modeling and analysis for the optimization scenarios considering the solar/storage combined with the hydropower generation plants offered alternatives for consideration by each community and are presented as follows:

- Full Resiliency (100% of the loads for 3-days) – the required amount of solar for this scenario is between 38 MW and 260 MW with between 271 MWh and 354 MWh of battery storage. Since 100 MW of Solar would cover on the order of five hundred acres, the solution is not likely a strong possibility for the community.
- Critical Load supportable by 5 MW of solar in each municipality (total 20 MW of solar) – the power budget for 365/24 service is 2.9 MW for all municipalities with a range of between 700 kW and 735 kW for the individual municipalities. The amount of total battery storage required to support the continuous outage and maintain critical loads is 44.8 MWh.
- With the capacities of solar and storage obtained in power budget analysis and considering the 100% of the loads of communities, the cost savings on electricity is 27.8% with a reduction of 47.9% of CO2 generated from the electricity generation compared to the base case.
- Changing the resiliency criteria to include supporting 100% of the loads for a 1-day outage – by allowing the storage to increase to an amount that supports a majority of the energy for the day. This scenario requires a storage size of 559 MWh. The cost of the battery yields a net cost increase of 21.1% with a 48.1% CO2 reduction compared to the base case. This scale of storage is on the order of grid-scale storage for large projects.

RECOMMENDATIONS

This feasibility study provides the basis for the next steps in the design and planning process including:

- developing specifications for equipment and systems; installation; project management
- defining specifications for updating distribution networks in the municipalities
- specifying connectivity to hydroelectric resources (38 kV line and substation)
- defining the low-level dynamic controls for individual municipalities
- defining communications and SCADA requirements
- specifying energy management system
- specifying metering and billing systems
- creating work force training required for installation, maintenance and operations

The Cooperativa will have to undertake these tasks to produce successful responses to Requests for Proposals and writing requests for proposals to procure equipment, systems and services.

This feasibility study is focused on the technical and economic decision making for the Microrred de la Montaña. The results of the modeling and analysis convincingly establish its feasibility. From this point forward the capabilities of the XENDEE/INL integrated platform can continue to be used for financial analysis, engineering analysis, and implementation management.

CONCLUSION

The Cooperativa Hidroeléctrica de la Montaña can use this feasibility study to justify and seek public and private financial support, to enable investments to establish microgrid capabilities that can provide the community with life sustaining services during catastrophic events such as hurricanes, earthquakes or cyberattacks, while producing an economic benefit to the combined municipalities of Adjuntas, Jayuya, Lares, and Utuado.

The feasibility study, based on the best available data on generation and loads, convincingly shows that substantial benefits will come from this project, as evidenced by the results of the modeling and analysis, most importantly resilience (local generation and islanding), reduction in electricity costs to customers (load-served LCOE to $.20 from $.28); most economic projected investment ($62.4 mil, excluding hydro plant); revenue for infrastructure development (power exports of $4.8 mil); and emission reductions

(47.9% savings as compared to emissions from central generation using fossil fuels in base case). Note since the completion of analysis using $0.285/kWh the cost of electricity has been increased to $0.334/kWh as of July 2022 further amplifying the impact the Microrred de la Montaña project will have on the municipalities.

RELEVANCE TO THE NET-ZERO MICROGRID PROGRAM

This study is a product of the Net-zero Microgrid Program (NZM) at Idaho National Laboratory supported by the Department of Energy, Office of Electricity Microgrid Program.[a] The study was used to demonstrated R&D that advances capabilities to evaluate the contributions of hydroelectric plants in microgrids. The study is an example of using carbon-free energy sources for generation in microgrids to transition away from carbon fuel-based generation that is prevalent in today's microgrids (see Figure ES-3). The study further provides an example for the potential for historically disadvantaged communities to utilize their available resources to provide resilience and economic benefit in their communities.

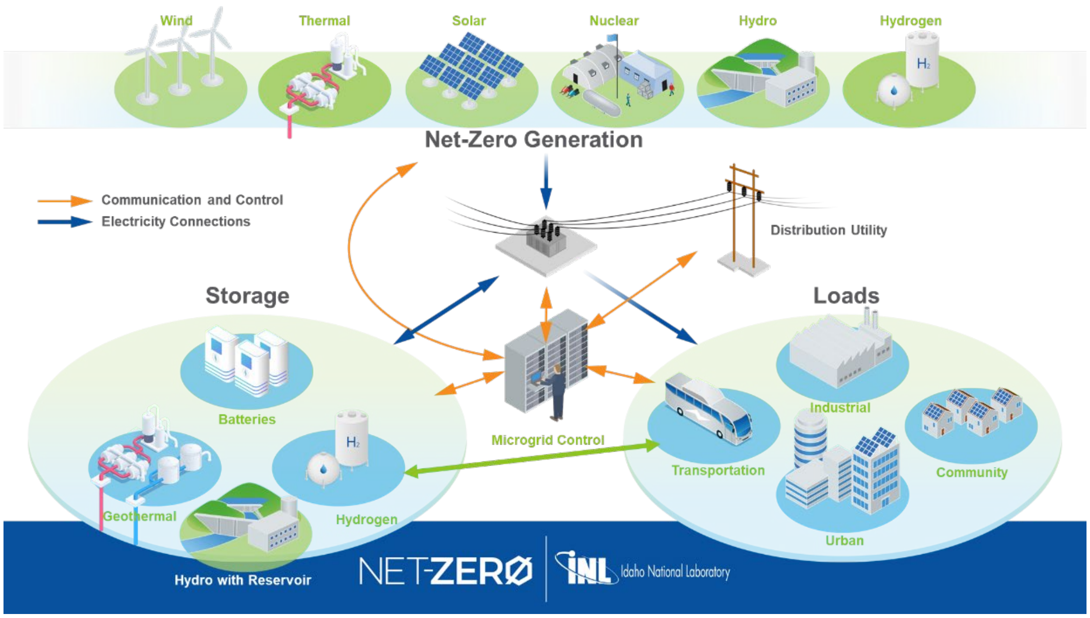

Figure ES-3. Net-Zero generation.

[a] McJunkin, Timothy R., and Reilly, James T. Net-Zero Carbon Microgrids. United States: N. p., 2021. Web. doi:10.2172/1831061.