Holistic Examination of Microgrid Applicability

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I. Introduction

This paper endeavors to provide an overview into microgrid systems as a modern approach to satisfying a variety of defined end-user goals for power consumers. Microgrids offer diverse applications that contribute to grid resiliency, remote electrification, renewable energy integration, and economic benefits. Recognizing the multifaceted advantages of microgrids is crucial for policymakers, energy planners, and communities to harness their potential and transition towards a sustainable, decentralized, and reliable energy system. This paper delves into the four aforementioned application areas, highlighting the opportunities and challenges associated with tailored microgrid implementation and paving the way for informed decision-making in future energy planning and policy development.

In 2022 before the COP27 Climate Change Conference, the IEA estimated that by the end of the year the global population of people without access to electricity would reach about 774 million and mark the first time in decades this metric would see an increase. The IEA attributed this to factors including the slowdown of new electric utility projects promoting energy access and grid connectivity to keep customer rates low during the Covid-19 pandemic. This is compounded by price increases for manufacturing off-grid energy assets (PV modules, inverters, batteries, etc.) along with population increases outpacing new utility projects. The IEA notes that the increasing population without electricity in 2022 was largely in sub-Saharan Africa, in which the World Bank estimates 58% of the population live in rural communities as of 2021, in comparison the United States estimates 20% of its population lives in rural communities according to a 2020 census[1-3]. Microgrids are an essential tool to improve quality of life for all people via energy access.

From our literature review, we determined that microgrids are implemented for many diverse purposes, often times more than one end goal, such as increasing renewable energy penetration *and* reducing energy costs. We recognize that each microgrid implementation mentioned in each section may have had initial planned purposes that also fall into one or more of the other three proposed classifications. We simply placed each paper in the section that most suited what we believed was the primary purpose for microgrid implementation.

A. System Overview

It is essential that we first define a microgrid before classifying them. As per the National Renewable Energy Laboratory (NREL) of the United States, "A microgrid is a group of interconnected loads and distributed energy resources that acts as a single controllable entity with respect to the grid." It is also essential to note that microgrid differ from bulk grid infrastructure by the fact that they are a smaller cluster of generation and load devices that can operate in islanded mode, that is, without connected to or relying on a stable bulk power system. Most microgrids do not incorporate high-voltage transmission line networks, as their geographic footprints are always orders of magnitudes smaller than power system interconnections that form the backbone of modern bulk power systems. The basic components of a microgrids are enumerated below. Note that not all microgrids implement all of these technologies; they are key technologies that help differentiate microgrids from bulk power systems.

1) Distributed Energy Resources (DERs): These are gas or diesel generators and renewable power generation sources such as solar panels, wind turbines, micro-hydro generators, or geothermal energy generators.
2) Energy Storage Systems: This is one of the most important components of a microgrid and where a lot of improvement can occur. They can be batteries, flywheels, or pumped hydro storage to help store excess energy produced by the DERs. Batteries today do not have the energy density and the cost efficiency to meet demands for large-scale grid integration and they will have to improve tremendously in the future.
3) Power Electronics Control Systems: These components are used to control and manage the flow of electricity in the microgrid, including inverters, controllers, synchronous condenser, and battery and power management systems.
4) Main Grid Interconnection: Though not possible in islanded, remote microgrids, it is common to interface a microgrid with the bulk power system to operate in grid-connected mode. The interconnection can be done with smart power electronics controlled switches or traditional relay devices at grid voltages. A transformer may be implemented at the microgrid or bulk grid side of connection.
5) Backup Generation: Smaller generation systems, such as diesel or natural gas generators, may be included to

provide backup power in the case of primary generation failure.

II. Islanded Microgrids for Remote Community or Industry Electrification

How do mining operations in the Andes mountain range keep the lights on and equipment moving despite being located hundreds of kilometers from bulk electricity infrastructure? Trucking gallons upon gallons of fossil fuels to these locations has been the status quo for decades. However, environmental concerns and cost saving measures may change this in the near future. There is immense potential for renewable energy to reduce massive amounts of carbon-based fuels used in extractive industries as the vast majority are sited far from traditional grid infrastructure and therefore difficult to electrify.

In contrast to electrifying remote extractive industry sites, rural and developing communities distanced from bulk grid infrastructure and have little capital to develop transmission networks. The sustainable development and electrification of rural communities requires strategies that respect human and environmental rights. They should also guarantee the involvement and empowerment of the community. One does not have to spend much time on the internet to find how negatively impacted remote communities have been by extractive industries (See: textitHuman Rights Watch hrw.org).

In this paper, we imagine a future where the electrification of a remote industrial site or mining operation can also benefit nearby communities during the life cycle of the contract and leaves people better off than they were before, e.g., energy independent. Though remote communities and precious mineral or oil conglomerates are often at odds, we believe an electrical "common ground" (nice pun) can mutually benefit both parties via the deployment of an isolated microgrid.

In their examination of the challenges within electrifying rural communities within sub-Saharan Africa, researchers from Carnegie Mellon espoused the benefits and applicability that microgrids can offer: an inherent proximity between generation sources to served loads (which minimizes power losses via transmission), flexibility and scalability for electricity deployment (by assessing local energy resources and configuring appropriate grid configurations), the possibility to save on infrastructure costs to connect to the nearest distribution network, and lastly, if automated control systems and storage systems are utilized (to complement intermittent renewable energy sources), better power quality and reliability can be achieved [4].

In previous microgrid implementations, remote communities have had their electricity needs met by solar energy for agriculture, water heating, medium-scale electricity generation for multiple homes, bolstering the tourism industry, and as essential to survival as community lighting and water pumping and purification infrastructure [19].

A. Alpaca Fiber Processing in Rural Chile

General Lagos is the northernmost settlement in Chile, located in the region of Arica and Parinacota. The population of 1,179 is entirely rural, and the nearest grid infrastructure is in Peru to the north. This, of course, presents international energy trading complications and therefore is infeasible in the short term. Luckily, northern Chile and the Atacama Desert has the greatest potential for solar in the world; it is a high-altitude desert with temperatures rarely surpassing 90 °F and 356 days of sunny, clear skies each year.

At more than twice the poverty rate in Chile, General Lagos is a community solely dependent on the ancestral practices of raising alpacas and other cattle. The aging population, lack of electric tools and facilities to sheer alpacas, and lack of reliable transportation to markets all have a major impact on the financial viability of their lifestyle. For this reason, a Chilean team of engineers from the Solar Energy Research Center in the capital city of Santiago devised an electric vehicle charging network and electrified sheering sites and fiber processing center for the community.

The final system was comprised of 144 photovoltaic panels generating a total of 46.08 kW and coupled with a 93.6 kWh battery storage. Electricity can be used to charge electric vehicles, heat water for alpaca fiber processing, and keep the lights on and sheering equipment buzzing at the facilities year round.

B. The Peruvian Case Study

The success of a microgrid to serve a community is not a uniform question and always guaranteed as M. Juanpera et al. recount in their multi-year survey of 9 electrification projects covering 6 rural communities in Peru's Cajamarca region. The survey, conducted in 2016 in two phases, posed a series of qualitative and technical questions to community members and local technical experts about the satisfaction and performance of the electrification project undertaken in their community (which were installed during 2008 – 2012); these electrification projects were either stand-alone systems for individual houses or microgrids, powered by either a single generation type (solar, micro-hydro, or wind), or a hybrid.

Broadly speaking, such inquiries covered the community members' perception of system performance (does the system provide enough consistent power for their existing and potential needs), system maintenance (are there sufficient resources and shared information to adequately maintain the project infrastructure), economic (how affordable are the costs of system maintenance, and is greater local business & economic activity occurring), social (does the system support a greater quality of life i.e. enabling the use of home appliances, longer hours of electric light for education) and environmental (how are local resources being utilized, how is system waste being managed).

The electrification projects were designed with the available resources nearby, the relative sparsity of the populace within the community, and the proclivities of that community for how resources should be used (e.g. the community in Suro Antivo opted to build a 25 kW micro-hydro plant on a river 500 m from the town center to serve 60 houses whereas a 4 kW micro-hydro plant installation was canceled in Morowisha as the river water there needed to be used for irrigation, so a 500 W wind turbine and eight 50 W PV panels were installed in the village instead). Some very sparse communities comprised of scattered households opted for individual electric systems such as those in Campo Alegre where each household received a 300 W wind turbine and 50 W PV panel.

A common theme that cropped up among the microgrid projects was the necessity of a cohesive community committed to active engagement in the equitable management, maintenance, and operation of their grid. Not all microgrid projects were successful – which was the case for the citizens of Alto Peru who faced a combination of technical and organizational challenges. Their system consisted of a combination of multiple electrifying projects (one 2 kW hydro-driven microgrid serving four houses and a school, one 760 W PV microgrid serving a health center and a handful of four other buildings, and a series of individual 95 W PV systems for the remaining 39 houses and 2 grocery stores). The variety of electricity sources yielded different qualities in supply (e.g. the hydro-plant could only operate 12 hours daily) which led to a sense of inequity and communal disengagement. This manifested in lower tariff payments to the organizing project enterprise, which in turn led to discontinued investment in the microgrid systems and worsening of system maintenance (a necessity in the operation of complex systems such as hydro-based generators and wind turbines). Eventually, due to system degradation, both microgrid projects were abandoned.

Whereas projects such as the one in Suro Antivo, which also utilized a micro-hydro microgrid, thrived to the point of expanding the grid and services to 40 additional houses and a school from two nearby communities in Ingatambo and El Chorro respectively. It's important to note that Suro Antivo benefited from communal factors and effective management (such as the provision of tools at home for basic system repairs) and the additional support of the local municipality providing oversight, technical resources, and guiding regulations (e.g. regulations for new-user infrastructure installation costs). These infrastructure improvements beget further communal planning and investment, allowing for more ambitious productive activities, necessitating an increased quality of electrical supply within a positive feedback loop. Overall the researchers noted that microgrids can provide long-term electrification and are applicable within higher-density communities given diligent planning (management of local resources and layout) and continuous engagement (technical training, maintenance, future development meetings, etc.) from the community and derive further advantage from partnering authorities and entities [5]

C. *Microgrids and Community Accommodation in Chile*

This need for and efficacy of considerate community engagement within remote microgrid planning was echoed in a paper by R. Palma-Behnke, et. al. The researchers focused on a subset of 79 candidate isolated communities in Chile for the applicability of microgrid-based electrification. The researchers propose the "coconstruction" method of microgrid design to fully incorporate the local populace at every level and stage of system planning and operation from conception to implementation. In this method, participation and project success are championed by an exchange of knowledge between the community (which shares its concerns, needs, understanding of the local social, cultural, economic, environmental, and territorial conditions) and the overseeing technical team conducting the project (which shares to the community its scientific understanding of designing and managing power systems, sustainability practices, etc.). This cross-training is imperative for empowering the community members to make well-informed decisions about its own power system. Within continuous meetings between the project teams and local community leaders the particular characteristics and boundaries of the microgrid system can come into focus, and gaps in local technical understanding and ability can be closed.

Within the same study, the co-construction method was employed to electrify the remote community of Huatacondo located within the Atacama Desert in northern Chile. In 2010, a project team was tasked with updating the village's electric network (which originally consisted of 10 hours of supply from a diesel generator) to accommodate continuous service to 27 households and the addition of a 23 kW PV array, a 3 kW wind turbine, a 120 kVA thermal generator, a 40-140 kWh BESS system (40 kWh represents the minimum level of charge for the battery banks), and a demand response management system. Fruitful dialogue between the project supervisory team and the community revealed the need to modify the proposed supervisory control and data acquisition (SCADA) system to accommodate community members that lacked the highly technical training to operate the SCADA system. Another result was the communicated importance of preserving the indigenous condor population and the potential threat posed by improper wind turbine installation. In response a simplified "Social SCADA" system was designed to provide a friendly user-interface for community technicians to monitor and interact with microgrid systems (generators, PV array, wind turbine, BESS system, demand response system) in real time. To preserve the condor population, protective cages were developed to encapsulate wind turbine rotors and the turbine was ultimately moved to preferably windier location 1 km beyond the village; consequent intermediate voltage lines (2 kV) for distribution were supported by a "microformer" made a transformer salvaged from a discarded microwave. As of 2018 the Huatacondo microgrid had advanced to support bidirectional EV charging (for custom crop harvester/trash transport vehicles), the successful replacement of the original BESS system and the incorporation a commercial inverter, with maintenance responsibilities completely shifted to a local company [6].

D. *Remote Microgrid Operation, High-level Design and Operation Considerations: System Sizing and Simulation in northern Canada*

Another case study in northern Canada conducted in 2018 provides further insight into some high-level design considerations and notes for constructing microgrids to serve remote communities[7]. In this study by F. Nejabatkhah et al. the set of available generation sources includes PV modules, battery energy storage systems (BESS) and diesel generators (DiGs). Whereas the composition (i.e. size) of these power sources is modeled as an optimization problem minimizing overall annual system cost (ASC) as constrained by the configuration and operation constraints (where the ASC is comprised of Annual Capital Cost (ACC), Annual Operation Maintenance Cost (AOMC), Annual Replacement Cost (ARC), Annual Fuel Cost (AFC) of the DiGs, and Annual Emission Cost (AEC) of the DiGs).

Within the study the researchers did not state which community they were examining but it can be assumed to be representative of a relatively small community with an aggregate average load demand of 1.4688 MW (with a standard deviation of 0.3318 MW, and a minimum load and maximum load of 0.8177 MW and 2.4536 MW respectively); for comparison the average power consumption in Ontario in 2018 was approximately 15,685 MW (as derived from the province's annual consumption) [8]. Secondly, while the cost and practical operation characteristics of available power sources were considered (accounting for PV panel efficiency and max power point tracking, protective battery state of charge (SOC) bounding, maximum and minimum power output for the DiGs, present-day value of capital costs, etc.) the demand of the community was treated as a singular load as previously described. Additionally given this hybrid system utilizes a BESS in its operation a charging strategy must be adopted, namely either a Load Following Control Strategy (LFCS) or a Cycle Charging Control Strategy (CCCS). In short a LFCS initiates charging whenever free energy is available (an excess of renewable power is present), and CCCS signals presently running and available DiGs and/or uses excess renewable power to maintain batteries at a specific SOC – this has the effect of reducing the amount of DiG start-ups and overall number of battery charge-discharge cycles (extending battery lifespans and reducing replacement costs) at the expense of greater fuel and emissions costs.

This particular study assumed PV modules with a nominal output of 340 W, battery banks with a 15 kWh capacity (and 15 year lifespan), and DiGs with a rated power of 1.145 MW, a particular CO2 emission factor of 0.634 kg/kWh, and applied carbon tax value which was $30/ton as of January 2018 in Alberta. Overall the researchers noted that BESS size is sensitive to its capital cost, a larger BESS size leads to fewer start-ups and operation hours of secondary DiGs (the first DiG will see an increase in operation due to the CCCS scheme), lower DiG operation hours (as fostered by PV and BESS utilization) results in lower AOMC and AFC (and AEC) as these costs depend on DiG operation hours and energy production. From this one can follow the logic of solving the constrained objective function to determine the unique size of their system components and derive similar perspectives.

E. *Remote Microgrid Summary*

Additional work from here would be to create a prescriptive categorization tool that first identifies a community as a suitable candidate for a microgrid (accounting for metrics and considerations such as population density, average power demand, demand per capita, cost of connecting to nearest source of electricity, available nearby natural resources, project budget, etc.) If deemed suitable then constrained minimization of costs of demand satisfaction can be used to identify the optimal generation sources among available options. This complete set of information should be provided to the target community so that community members can effectively understand the challenges of their power system, the proposed design, and then articulate and uphold the priorities and decisions of the community while meeting their energy needs. Further work could include a technical comparison of different microgrid facilitating technologies and tools (communication architectures, smart meters, intuitive management system interfaces, etc.) to suggest the appropriate system hardware and software choices.

III. Microgrid Deployment for Energy Resilience

Blackouts are not only disastrous for residential customers, like most are familiar with, but at the power system and critical infrastructure levels blackouts are extremely costly and can even jeopardize national security. It does not matter if a blackout is caused by a hurricane, vegetation overgrowth to transmission lines, or power system operator errors, one thing is for sure: blackouts will happen. Very few industries remain where losing electricity is but a minor inconvenience; every business that is connected to the internet, every manufacturing facility, and almost every bar, club, restaurant, stadium, theatre, and arts venue is crippled without electricity. Nations across the globe recognize the importance of energy in national security, and many are now turning to locally-sourced energy for critical infrastructure microgrids to ensure greater electricity reliability than what the bulk power system can provide.

From a bulk power system perspective, distributed energy resources can increase grid resiliency from cyber-physical threats by radically increasing the number of generators on the system. In theory, a power system that relies on 100 large-scale generators is easier to bring down via coordinated hacking or physical attacks than one powered by millions of small-scale distributed energy resources. On the other hand, though, a system with millions of inverter-based generators online is more difficult to control and ensure stability than our status-quo steam and hydro bulk generation mix. Microgrids for critical infrastructure are not immune to cyber attacks, but, due to their smaller footprint, it is conceivably easier to oversee an entire microgrid system in real time than a bulk power system.

Airports, water treatment facilities, vehicle traffic systems, military bases, and hospitals are all prime examples of essential infrastructure that must operate at all times for the safety and security of human populations. For this reason, microgrids for these industries utilize fossil fuels for electricity generation because they are the most reliable energy sources and are easier to store in bulk than renewables. Renewable energy can be a part of the generation mix, but it is essential that critical infrastructure has its energy needs met in the absolute worst-case scenarios. Very few people would be willing to trade the guarantee of safe, clean drinking water or an available hospital bed for reduced greenhouse gas emissions from these sites.

A. Pittsburgh International Airport Microgrid

In the wake of multiple costly, crippling airport power outages like Adelaide, Australia in 2016 and Atlanta in 2017, Pittsburgh International Airport (PIT) announced in 2019 that it would become the first airport in the United States to be able to support its own energy demand on-site. Taking advantage of its unique location in the foothills of the Appalachian mountains, the Allegheny Country Airport Authority [16].

Secure flight takeoff, landing, and taxi would not be possible without electricity to light up the runway. In addition, security systems like bag scanners operated by the Transportation Security Administration in the US cannot operate without electricity. No government or private airline company should be expected to take the massive risk of flying without proper security checks for its passengers. For these reason, the PIT microgrid takes advantage of three energy sources to guarantee 24/7/365 uptime:

1) A 2.5 MW peak solar farm on airport property
2) 20 MW of natural gas generation potential supplied by a Peoples Gas Distribution lines from a natural gas source on site
3) A traditional 3-phase transmission system connection to the bulk power system (PJM)

As can be assumed by the generation mix, this microgrid was never planned to be 100% renewable. The primary motive for the PIT microgrid was to guarantee a reliable electricity source in the event of grid failure. In its first year of operation between June 2021 and July 2022, the microgrid saved PIT over a million dollars in energy costs [17]. This remarkable benefit was originally unexpected; the primary and sole motivation of the PIT microgrid was to ensure electricity reliability, but because microgrids with renewable energy and local small-scale gas generation sources can act as a demand response and ancillary service when connected to the bulk grid, the project was not only affordable, but also appears to be profitable in the long term if gas and electricity price trends continue.

B. The Philadelphia Navy Yard Microgrid

Another prime example of ensuring electrical reliability of critical infrastructure is at the Philadelphia Navy Yard in South Philadelphia, Pennsylvania. The Navy Yard Microgrid is owned by the Philadelphia Industrial Development Corp (PIDC) and a project cost of $95 million to PIDC with an expected ROI of 20% [18].

The project was planned and implemented in partnership with the Philadelphia Electric Company (PECO) and the independent system operator of Pennsylvania (i.e. PJM) to ensure that the microgrid would be beneficial to both the Navy as well as the bulk regional power system as a whole. Over 12,000 workers visit the shipyard each day, both military personnel and civilian thanks to the dynamic urban development open to the public and home to plenty of history, architecture, events, parks, and riverfront dining options.

The microgrid is powered by 6 MW natural gas fired reciprocating engines and 2 MW of roof-mounted and car-shade structure photovoltaic arrays, as well as 1 MW of battery storage. They are currently in the process of installing 0.8 MW of fuel cell capacity. The renewable and low-carbon generation mixture provides a total reduction of greenhouse gas emissions by a projected 13%, even with the continued growth and expansion of its 1200 acre footprint.

The Navy Yard microgrid is an active participant in PJM's energy market by providing up to 16.7 MW of demand response, for which it is paid. Microgrid managers at the Navy Yard save PIDC money by being on call from PJM to supply energy to the bulk grid as well as supplying their own power locally when electricity rates are high during peak demand periods. They also participate in real-time and future energy trades.

Most interesting and relevant to our coursework this semester is the Network Operations Center located at the Navy Yard. This center holds the local microgrid operator rooms and handles thousands of data points from over 900 smart meters on campus. Nearly 100 of these smart meters utilize advanced metering infrastructure capable of sending event data every 20 seconds to the control center [18]. This sort of infrastructure is essential for reducing the risk of microgrid outages and increasing system situational awareness by measuring and validating power quality, voltage sags and spikes, and potential faults on the grid whether it is connected or isolated from the bulk power system.

IV. Microgrid Implementations for Economic Benefits

There are four main factors to microgrid economic feasibility as explained in the following subsections *A* to *D*.

A. Pro forma cash analysis with financial assumptions

A pro forma cash analysis is a financial analysis that estimates the expected cash inflows and outflows of a business or project over a specified period of time. It typically includes revenue projections, capital expenditure forecasts, operating expenses, and cash flow projections. Just like any other project before establishing a microgrid a pro forma cash analysis needs to be conducted to assess feasibility of the project. Net present value (NPV) is the value in today's dollars of all future cash flows (both positive and negative) generated by a project, discounted back to their present value using an appropriate discount rate. If the NPV is positive, the project is expected to be profitable and worth pursuing.

B. Optimization for capacity or sizing of generation sources

[12] demonstrates that the optimal capacity or sizing of generation sources can be assessed by calculating the Annual System Cost (ASC). The ASC includes Annual Capital Cost

(ACC), Annual Operation Maintenance Cost (AOMC), Annual Replacement Cost (ARC), Annual Fuel Cost (AFC), and Annual Emission Cost (AEC). The two prominent costs among the costs are ACC and AOMC can be calculated as follows,

1) Annual Capital Cost

$$ACC = C_{cap} \times CRF(i, y) \tag{1}$$

where C_{cap} is each component capital cost in \$, y is the project lifetime in years, CRF is the capital recovery cost (a ratio used to calculate the present value of an annuity), and i the is real discount rate. The calculations of CRF and i are presented in (2) and (3).

$$(i, y) = \frac{i \times (1+i)^y}{(1+i)^y - 1} \tag{2}$$

$$i = \frac{i' - f}{1 + f} \tag{3}$$

where i' is the nominal loan interest (or nominal discount rate) and f is the annual inflation rate.

2) Annual Operation and Maintenance Cost

$$\begin{aligned} AOMC_{com} = OM(\$/kW/h) \times P_{com}(kW) \times \\ \text{operation hours}(h/yr) \end{aligned} \tag{4}$$

where, OM is the operation maintenance cost, P_{com} is the output power of each generation source. The optimal of number of PV modules and battery banks for the case study presented in [12] was estimated by solving an optimization problem that sought to minimize the ASC.

C. Optimization of operations

There are several examples of advanced controls and demand-side technologies that can help optimize costs in the energy industry. Here are a few:

1) Energy Management System (EMS): EMSs are software systems that enable organizations to monitor and manage their energy consumption in real-time. By providing detailed energy data and analytics, EMSs enable organizations to identify energy waste and optimize their energy use, resulting in significant cost savings.
2) Building Automation System (BAS): BASs are advanced control systems that automate the operation of various building systems, including heating, ventilation, and air conditioning (HVAC) systems, lighting, and security systems. By automating these systems, organizations can optimize energy use and reduce energy waste, resulting in cost savings.
3) Predictive Maintenance: Predictive maintenance systems use machine learning algorithms to predict equipment failures before they occur. By identifying and addressing potential equipment failures before they happen, organizations can avoid expensive downtime and repairs, resulting in cost savings.
4) Energy Storage System (ESS): ESSs use advanced control systems to store energy during off-peak times and release it during peak demand periods. By optimizing energy storage and release, organizations can reduce their reliance on expensive peak pricing charges from utilities and optimize their energy use, resulting in cost savings.

Schneider Electric's Boston One Campus Microgrid proposes advanced controls and demand-side technologies in the form of predicting weather forecast data and leveraging other operational site, as it enables energy systems to respond to changing conditions in real-time [13]. By leveraging weather forecast data, the microgrid can predict the amount of solar energy that will be available and the energy demand at the site. Based on this information, the microgrid can adjust the operation of various energy assets to ensure that energy is produced and consumed in the most efficient manner possible.

The microgrid also leverages other operational site data to optimize energy use. For example, the microgrid can adjust the charging of EVs based on their expected usage patterns and the availability of renewable energy. This helps to ensure that EVs are charged when renewable energy is available, reducing the use of fossil fuels and saving money.

D. Demand side management (DSM), especially in emerging economies

Demand side management (DSM) is an important strategy for managing energy demand and optimizing energy use. DSM can be implemented by energy conservation, peak shifting, use of onsite generation among others. In emerging economies, DSM can be especially important, as it can help reduce energy costs and increase energy efficiency during times of crisis.

One example of DSM in emerging economies is the use of cellular networks for communication in advanced metering infrastructure (AMI) [14]. AMI systems use smart meters to collect energy usage data and transmit it to utilities for billing and other purposes. By using cellular networks for communication, utilities can reduce the cost of deploying AMI systems, as they do not need to build out their own communication networks.

However, the use of cellular networks can also create congestion and increase traffic on the network, which can lead to increased costs. To address this issue, utilities can use DSM strategies to optimize their use of cellular networks. For example, utilities can choose cellular base stations with low traffic to reduce the load on the network and minimize costs.

V. Microgrid Implementations for Increased Renewable Energy Penetration

The world is experiencing a significant shift toward sustainable energy sources to mitigate climate change and reduce reliance on fossil fuels. Renewable energy, including solar, hydro and wind power, plays a crucial role in achieving these goals. Microgrids can help overcome some of the challenges associated with the intermittent nature of renewable energy sources. They can also prioritize renewable energy to reduce our reliance on fossil fuels and decrease greenhouse gas emissions.

Within the US, Alaska's abundance of natural resources has made it an early adopter of microgrids to integrate renewable energy. They help against high energy costs of diesel generators and vulnerability to extreme weather events. Incentive programs and policies promote the adoption of renewable energy and microgrid systems, encouraging the diversification of energy sources and reducing dependence on fossil fuels. Today, out of the 200 microgrids in Alaska, more than 70 incorporate renewable energy, including small hydro, wind, geothermal, biomass, and solar projects.

A. *The City of Nome, Alaska*

Nome is an isolated community located on the western coast of Alaska. The electricity grid in Nome is an islanded microgrid, powered by a local wind farm of 2.7 MW capacity with the potential to add 2 MW of low-temperature geothermal power. Currently, the wind farm's fluctuations are bolstered by diesel generation.

There are still challenges to overcome. Researchers investigated the interaction between wind, geothermal, and diesel energy resources. They simulated different capacities of geothermal plants and observed that the addition of geothermal energy to the grid had an impact on the amount of wind power that could be accommodated. Specifically, the integration of geothermal energy led to an increase in unused wind power, referred to as "spilled wind." The simulation model indicated that the benefits of increasing geothermal generation diminished after reaching a capacity of 2.75 MW. At that point, the reduction in diesel generation became less significant as a substantial amount of renewable energy remained untapped. Furthermore, scenarios were explored where smaller diesel generators were introduced to the grid, resulting in a more substantial decrease in diesel generation.

Researchers focused on exploring energy storage solutions, such as flywheels and batteries, to compensate for the loss of regulation services typically provided by diesel units. As renewable generation increased, the load on the diesel generators decreased, necessitating their regulation to account for the variable output from wind generators. However, operating diesel generators at reduced loads can lead to reduced efficiency, higher maintenance costs, and a shorter lifespan. To mitigate these challenges, energy storage systems were incorporated into the grid to provide spinning reserve capacity. The addition of energy storage resulted in a greater reduction in diesel generation and alleviated some of the stress placed on the diesel generators caused by the integration of geothermal generation. This is a recurring theme in renewable energy, energy storage is a major challenge around the world. [9]

B. *The City of Kodiak, Alaska*

Kodiak Electric Association (KEA), an islanded microgrid serving the community of Kodiak, Alaska, aimed to optimize their energy generation system by integrating renewable sources and reducing costs. KEA constructed a significant wind farm on Pilar Mountain, featuring six General Electric wind turbines with a capacity of 1.5 MW each, making it the largest wind farm in the state. However, before KEA could expand their wind power capacity, they needed to develop a strategy to ensure smooth integration of power systems and implement energy storage solutions for both short-term and long-term needs.

To address this, KEA conducted a review of various energy storage options suitable for their grid, including pumped hydroelectric, batteries, flywheels, and compressed air energy storage. Among these options, the most promising solution was determined to be a battery storage system. This choice was based on factors such as the maturity of the technology, successful implementation in other Alaskan communities, and overall cost-effectiveness. Further investigation into short-term battery storage was conducted using a dynamic power-flow model, which indicated a potential improvement in frequency response time, albeit a modest one.

Recently, Kodiak Electric Association installed a 2 MW flywheel storage system in addition to an existing 3 MW battery system. These systems were designed to stabilize the 9 MW of installed wind capacity on the grid. The combination of wind power, existing hydropower, and the integrated storage systems positions Kodiak as the first community in Alaska to achieve nearly 100% renewable generation throughout the year. This accomplishment not only optimizes the balance between wind, hydro, and diesel generators but also enhances efficiency and reduces overall costs for the KEA grid. [9]

C. *The Island of St. Paul, Alaska*

St. Paul Island, located in Alaska's Bering Sea, is home to an innovative wind-diesel hybrid microgrid developed by TDX Power. TDX Power, a subsidiary of the St. Paul Island Tanadgusix Village Corporation, installed the system to supply electricity and space heat to an airport and industrial complex, which includes airline offices, equipment repair space, and storage facilities. The microgrid comprises three 225 kW wind turbines and two 150 kW diesel gensets. Remarkably, this system has been successfully operating for over 15 years, with the wind turbines capable of supplying up to 100% of the grid's power without the need for a battery system.

The St. Paul Island microgrid ensures a continuous power supply by producing excess wind energy during periods of resource availability. This surplus energy is then directed towards secondary heating loads. To maintain grid stability, the system incorporates a 300 kVA synchronous condenser, and more recently, a high-performance flywheel. These components help regulate the grid and ensure a consistent power supply.

In 2009, TDX Power approached ACEP (Alaska Center for Energy and Power) to assess alternative technologies that would allow the utilization of excess wind energy to power a fleet of electric shuttles for tourism and residential transit on the island. The concept of plug-in electric vehicles presented an excellent opportunity to manage loads efficiently and maximize the utilization of variable resources like wind power. The integration of plug-in electric vehicles on St. Paul Island could complement the existing managed thermal loads and leverage the abundant wind resource to reduce reliance on imported fuels for transportation. This solution is particularly suitable for areas with limited road networks and short commuting distances, as is the case on St. Paul Island.

The potential use of plug-in electric vehicles offers a promising avenue to further enhance the integration of renewable energy sources, utilize the island's ample wind resource, and decrease the reliance on imported fuels for transportation on St. Paul Island. [9]

D. Isolated Islands in the Philippines

The Philippines is home to thousands of remote off-grid islands that are too distant from the mainland, making it costly to connect them to the main electricity grid. Consequently, there are 5.5 million people residing on these islands who lack reliable access to electricity. Currently, diesel generators are commonly used to power these islands, but as fuel costs continue to rise, greater subsidies will be required to sustain this energy source. Hybrid renewable energy systems (HRES) offer an alternative with reduced reliance on fuel and generation costs.

Islands such as Patongong Island, Lapinigan Island, Balabac Island, and Sibuyan Island, represent a range of peak electrical demand from 4.4 kW in Patongong Island to 3.2 MW in Sibuyan Island. These islands serve as representative of the broader off-grid island context in the country, highlighting the vastly different kinds of microgrids that exist and need to be built in the future.

Research indicates that the large Sibuyan Island could achieve profitability at an electricity price of 0.2 USD/kWh, similar to the mainland rate. This suggests that subsidies for large islands can potentially be phased out. However, with an internal rate of return (IRR) of only 11% and a 13-year payback period, the financial attractiveness to private investors is limited. Increasing electricity prices could help alleviate this concern. On the other hand, smaller islands like Patongong Island would still require subsidies, as profitability is only achieved at 1.5 times the mainland rate. This highlights the importance of subsidies in ensuring energy access for small off-grid islands and the need to attract private investors. The deploying of HRES in off-grid island contexts for sustainable energy access in the Philippines is still an ongoing problem [11].

Alternatively, with the abundance of solar resources in the Philippines, solar microgrids have been successfully implemented in various regions. Solar microgrids are well-suited for remote and off-grid. By deploying solar panels coupled with energy storage systems, these microgrids can operate independently, providing electricity to communities that were previously underserved. They have brought electricity to off-grid islands, rural communities, and even disaster-prone areas, improving the quality of life and enabling economic opportunities. Solar microgrids have also played a crucial role in powering critical facilities such as schools, health centers, and communal spaces.

However, there are still some challenges, such as the upfront costs of installation and ensuring the sustainability of operations and maintenance. Government support, policies, and innovative financing mechanisms can play a crucial role in overcoming these challenges and scaling up solar microgrid deployments across the country. [10]

VI. Conclusions and Next Steps

This paper has examined the constellation of microgrid facets and the feasibility of their implementation within a variety of case studies, highlighting various end-user priorities, opportunities, and challenges within the categories of grid resiliency, remote community electrification, integration of renewable energy systems, and economic feasibility. Considering the dynamic advantages of microgrids is crucial for policymakers, energy planners, and communities to harness their potential and transition towards a sustainable, decentralized, and reliable energy system.

Additional work from here could include the creation of a prescriptive categorization tool that first identifies a community as a suitable candidate for a microgrid based on their composition, priorities, and budget. Such further work could include a technical comparison of different microgrid facilitating technologies and tools (communication architectures, smart meters, intuitive management system interfaces, etc.) to suggest the appropriate system hardware and software choices. In addition, improvements to battery technology can help include a greater number of renewable energy components to microgrids.

Despite the often-criticized intermittency of renewable energy resources, renewables have been implemented as DERs in microgrids for critical infrastructure like airports and military bases. These applications do not prioritize sustainability to focus on maximizing electrical energy reliability and security. It is essential, however, that we do not avoid renewables altogether for these applications with the planet in mind. It is short-sighted, however, to imagine a near future where even critical infrastructure is powered completely by renewable energy. Beyond environmental concerns, microgrid implementations for critical infrastructure are more appealing when considering their potential for ancillary service participation as an added cost reduction and potentially profit-driving aspect.

The future of renewable microgrids is promising, with advancements in technology, policy support, and increased awareness of sustainability. These decentralized systems will play a vital role in transitioning to clean energy, enabling energy self-sufficiency, ensuring critical infrastructure energy availability, and empowering local communities to actively participate in the energy transition.

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