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A Literature Analysis of Microgrid Optimization Studies

An Honor's Thesis Written by Izzy Medeiros
Class of 2023

Advised by Dr. Weiwei Mo

May 16, 2023

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Introduction

A microgrid is an energy grid serving small areas and can sustain itself using renewable energy [1]. Most of the world is currently powered by the utility grid, which receives energy from power plants that are usually dependent on fossil fuels. Microgrids not only take advantage of renewable sources, but they also offer energy reliability. During extreme winds, for example, a centralized power system may fail, leaving those reliant on it without power. Most microgrids can disconnect from the main grid during these events and continue to operate, making them more flexible than the main grid. Thus, we look towards microgrids as the future of reliable energy.

Because of their sustainable nature and resiliency, microgrid application is expected to rise. Currently, microgrids supply less than 0.2% of electricity in the US, but this is expected to nearly triple in the coming years [2]. Another reason why microgrids are gaining popularity is because of their consumer benefits. The cost of electricity from the utility grid is extremely variable, leaving consumers to pay based on seasonal rates [3]. Microgrids have more predictable costs [4], and in some cases can even earn consumers money if they choose to sell energy back to the grid. Optimization studies balance the trade-offs to achieve a certain result [5]. Researchers investigate ways to improve existing knowledge of these grids, so they use optimization techniques to make the microgrid of study as efficient as possible. In most cases reviewed in this study, researchers chose to manipulate input variables in order to achieve economic and/or environmental optimization.

Previous review studies were used in this analysis to point towards additional publications. Some review publications that have arose in this analysis have investigated energy management, planning, energy storage methods, and component sizing. This review paper differs from most review publications, as it takes stock of current microgrid research and directs future research by highlighting gaps in the knowledge. The goal of this paper is to observe the following as it pertains to microgrid study: locations pioneering research, common included renewable energy sources, popular types of battery storage, and optimization objectives. The rest of this paper is organized as follows: methods, results & discussion, followed by a major findings section.

Review Method

Google scholar was the main search engine in finding current literature regarding microgrids. Primary journal publications including Elsevier, IEEE Xplore, and Springer were used in this literature review. Keywords used include: microgrid optimization, microgrid life cycle analysis, and islanded microgrids. This study began with 48 publications of interest, which was narrowed down to 36 that fit within the scope of this study. Results were refined based on relevance to the research conducted by Dr. Weiwei Mo of the University of New Hampshire and her work on the hybrid microgrid of Shoals Marine Laboratory of the Isle of Shoals. Review papers found in this search were also used to further specific research but were then eliminated from analysis. Papers that also had no optimization objective were rejected from analysis as well. Microsoft Excel was used to organize the publications based on methods, optimization objectives, etc. The rest of the paper is organized as follows: the motivations of previous studies are outlined, followed by the design of researched microgrids, optimization objectives, and lastly, concluding statements.

Motivations

There is a promising future for renewable based hybrid microgrids; a sustainable alternative to the utility grid that can provide reliable energy to communities. Typically, hybrid microgrids consist of photovoltaic (PV) panels, a wind turbine, a battery energy storage system, and a diesel generator used in the event of low renewable generation. Hybrid microgrids should meet the demand without being wasteful or harmful to the environment. For example, purchasing redundant battery storage raises the economic and environmental costs of the microgrid. Thus, optimization is critical in microgrids to reach a balance between objectives. The research presented in the reviewed publications are ultimately conducted to improve global infrastructure and to make energy more accessible at low economic and environmental costs. This paper reviews the current literature regarding microgrids to find gaps in research knowledge and to influence the direction of future studies.

Results

Location of Microgrid Systems

Each of the populated continents have conducted microgrid studies on a real system. Fourteen of the 36 publications used for analysis involved the study of a real microgrid, the locations of which are shown in Figure 1. From this data, Asia is leading the way in renewable microgrid research, followed by Europe. Southeast Asia is eager to develop renewable microgrids due to their areas of large and dense populations with a lack of access to the utility grid. The Microgrid Deployment Tracker 3Q21 has ascertained that 59% of microgrids in the Southeastern Asia region are stationed in rural areas with unreliable power sources [6]. Extreme weather events can disrupt the connection of Southeast Asian islands to the utility grid, perpetuating the unsafe conditions of these events. By investing in research in smaller, more flexible energy schemes, these countries are looking ahead to the future and prioritizing sustainable and reliable infrastructure. Microgrids, if not otherwise operating in standalone mode, can disconnect from the main grid in the event of a weather threat [7]. Communities once at risk of long-lasting power shortages can be adaptable and strong in the face of the effects of climate change.

Following Asia is one continent with a surprising amount of interest in microgrid studies: Europe. Because Europe is a very developed area with robust infrastructure and reliable power, research conducted in Europe concerning renewable microgrids may be for another reason. The EU has a goal of climate neutrality by 2050, which would require zero net greenhouse gasses emitted by Europe by then [8]. There is also an emerging market to employ renewable microgrid systems, as excess energy can be sold back to the main grid for profit. During the forecast period of 2022-2023, the Europe microgrid market is projected to generate $1.1 billion in revenue [9]. Though large-scale employment of microgrids would be both economically profitable and would help Europe to reach its climate neutrality goal, these are not the sole reasons why Europe is highly invested in microgrids. In 2019, the United Kingdom suffered a devastating blackout leaving hundreds of thousands of homes without power, due to the failure of two power plants [9]. As a result, an emphasis was placed on research into the benefits of microgrids for their reliable and flexible power.

Africa, South America, and Australia compete for the continent with the third highest microgrid research. It is worth noting that, though the continent of Australia is only represented twice, it was the only country with more than one microgrid publication. This may not only be attributed to the fact that Australia is both a continent and a country, but also because it has the smallest population of all the populated continents [10]. Research for microgrids in Australia is on the rise, however. In the 2020-2021 Federal Budget, a $50 million Regional Australia Microgrid Pilots Program was announced to improve the development of microgrids [11]. The government in Australia is also concerned with power access to remote communities, as well as maintaining robust infrastructure during natural disasters. South America also has a rapidly growing market for microgrids. A research report published by Triton Market Research announced a forecasted a compounded annual growth rate of 10.61% of the Latin American microgrid market for the years 2022-2028 [12]. The Middle East and Africa follow closely behind South America, with a projected compounded annual growth rate of 10.56% [13]. Communities worldwide will depend and spend less on the utility grid and will turn to using microgrids as a better alternative.

It is fascinating that North America is lagging behind within the scope of this study, according to Figure 1. The microgrid market of North America is predicting a 13.5% growth rate through the year 2023, as investments in microgrids have reached $6.4 billion [14]. In the U.S., the 2021 Texas grid collapse has reinforced the need for implementing microgrids. A harsh winter storm left more than 2.5 million people without access to power or heat, resulting in 20 reported deaths. Subsequent power plant failure leads to widespread system failure, which is one of the reasons why there is such a high investment in microgrids [15]. The Department of Energy Microgrid Program Strategy was enacted as a first step towards improving the breadth of microgrid penetration by 2035 [16]. There is an emphasis on microgrid research globally due to the impending impacts of climate change and their disruption on community power. However, it is difficult to make very strong assumptions based on this data because there are only 14 publications that used real microgrids.

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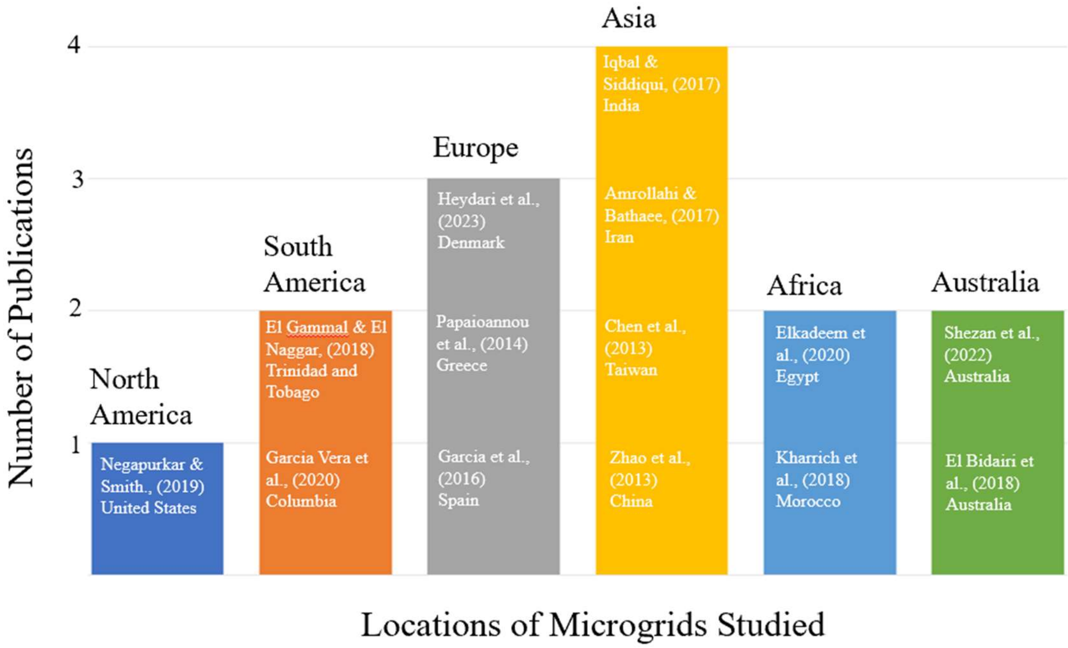

Figure 1: Locations of Studies Conducted on Real Microgrids

Renewable Energy in a Microgrid

The most common combination of renewable energy included in a microgrid used PV panels and a wind turbine (WT), which is made evident in Figure 2. Both photovoltaic panels and wind turbines have been widely researched and have become commercially available to the average homeowner. The upfront solar panel cost ranges between $15,000 and $25,000 and can cost $3 to $5 per watt, where wind turbines cost about $8 per watt [17]. Wind turbines are more expensive and will require a high maintenance level conducted by trained technicians. However, solar panels can be more widely applied as sunlight is available everywhere. When solar panels receive sun, they can only harness about 20% of solar energy where turbines can harness 50% of kinetic energy from wind [17]. Another benefit of wind turbines is that, in areas with a lot of wind, they can continue to produce energy through the night, while solar panels are limited to daylight [17]. This may be why one author chose to study a microgrid that only used wind as a renewable source. Both of these technologies have their benefits and drawbacks as renewable energy sources, but their environmental impacts must be studied through a life cycle analysis in order to get a more wholistic understanding of their respective impacts. The production and disposal phases of a wind turbine are very taxing and create a hazardous waste equivalent of 230 million people [18]. Solar panels also have environmentally taxing production and disposal phases because they require at least 19 rare minerals [19]. These drawbacks must be discussed when talking about microgrids to inform the public that microgrids do have serious environmental impacts associated with their production and disposal phases. Comparatively, however, these effects are much less than that of combusting fossil fuels.

One interesting source of renewable energy applied to three microgrid studies is using energy generated from biomass. This is the fourth largest renewable source following the aforementioned solar, wind, and hydro power, and the world's net electricity production from biomass energy is greater than 117 GW [20]. Biomass energy involves burning plants, wood, and waste to create heat electricity, or biofuel [21]. Another way biomass produces energy is through anaerobic digestion. In this process, waste is digested by anerobic bacteria, which produce gasses that can be cleaned and used for energy generation [22]. In 2021, biomass provided 5% of the US energy consumption and exported more biomass energy than it received in imports [23]. The United Nations Intergovernmental Panel on Climate Change, the U.S. Department of Energy, and the European Union have supported biomass as a means of alleviating climate change [24]. One major drawback of bioenergy generation is that a lot of farmland would be needed to grow enough crops for bioenergy to compete with other renewable energy [25]. So, the future of bio-energy may remain in the balance.

There was also minimal research into harnessing ocean energy. It is rare for a community to use wave (ocean) energy because it is so expensive. However, in 2020, Canada initiated an Ocean Energy Smart Grid Integration Project, and as such is trying to implement ocean energy into remote islanded microgrids [26]. The University of Victoria's Pacific Regional Institute for Marine Energy Discovery was given a $730,000 grant to develop a microgrid using wave energy for Nootka Island [27]. Without sufficient funding, however, this would not be feasible for a community.

Zero studies within the scope of this project investigated small scale community-based hydropower, but there is still debate as to whether or not hydropower is considered renewable energy. Controlling the flow of rivers through dams and reservoirs to harness hydropower has large ecological impacts, as fish cannot travel through them, and they block sediments from depositing downstream. Most recently, hydrokinetic technology is being investigated. It has minimal environmental impacts, and it is considered renewable because it captures hydrokinetic energy from rivers not from waves or tides to generate electricity, and no dams are involved [28]. This in-flow design technology is passive in nature, and causes little ecological harm, making hydrokinetic technology a viable option for future research.

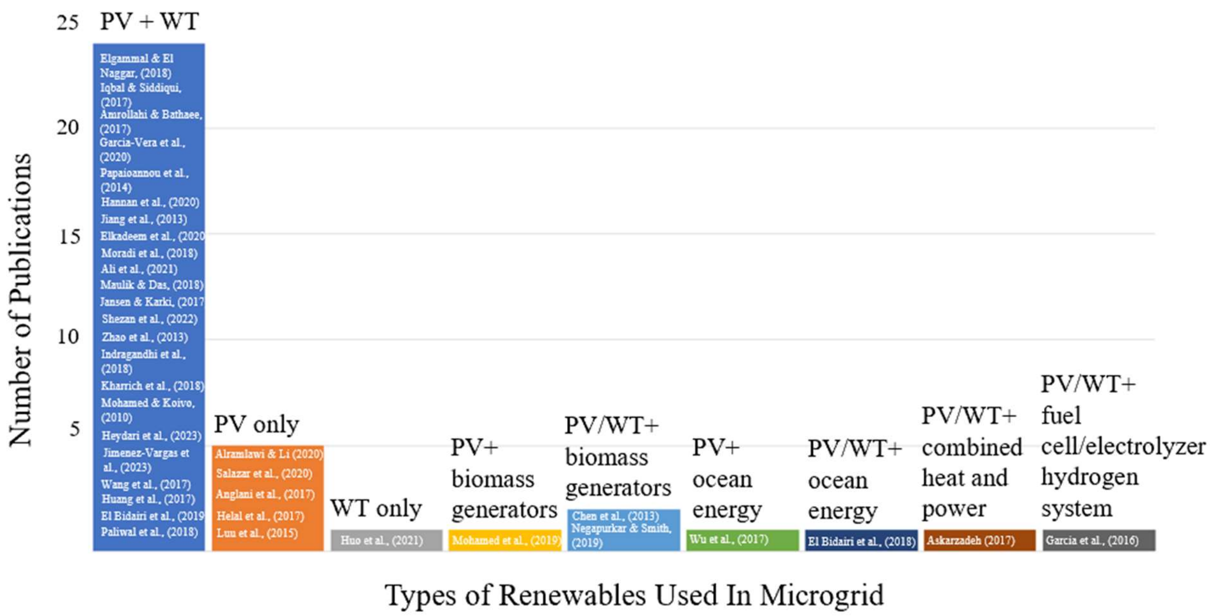

Figure 2: Combinations of Renewables Used in Microgrid Design

Standalone and Grid Connected Systems

Most publications reviewed were studied standalone systems, shown in Figure 3. This could be due to the directed search keywords used, such as “islanded microgrid”, to obtain the publications for review. Minimizing reliability on the utility grid by using a standalone microgrid is cost effective and better for the environment. However, these standalone systems require a large number of batteries with high capacity, which must be replaced multiple times throughout a microgrid lifetime. These systems also require frequent maintenance, which increase the overall microgrid cost. In the grid connected case, a microgrid can receive services from the utility grid [29]. These systems still have energy storage and renewable sources, while also maintaining the ability to rely on the grid. When renewable microgrids are grid connected, unused or unstored renewable energy may be sold back to the grid for a profit or may otherwise lower the cost of the microgrid. Only three authors of this review studied microgrids in both the standalone and grid connected modes of operation.

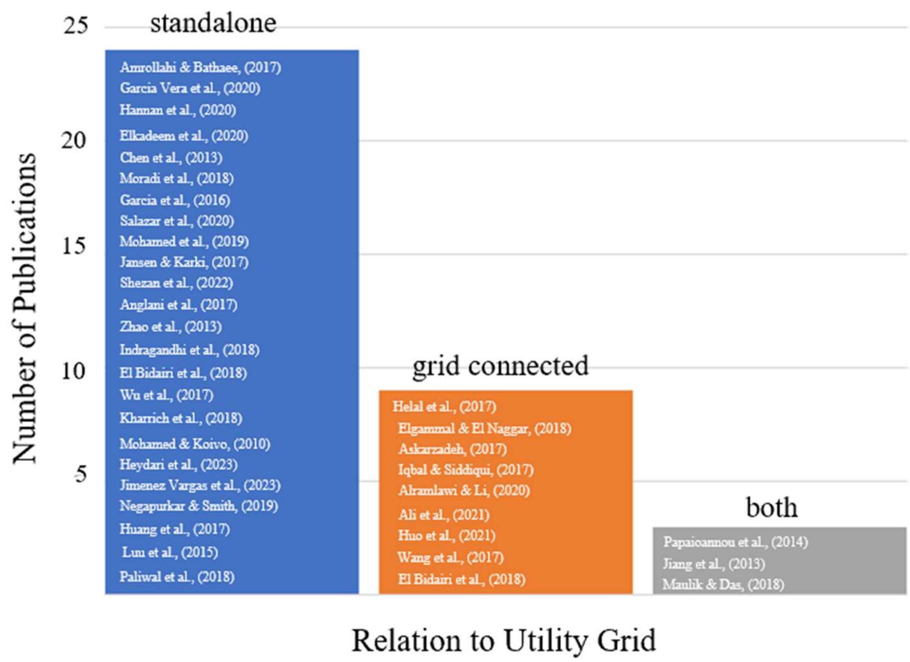

Figure 3: Microgrid Relation to Utility Grid

Energy Storage

Most authors in this review used batteries but did not specify the type of battery used for energy storage in a microgrid, as shown in Figure 4. The most common identified battery is lead-acid, then lithium-ion, because, although lithium-ion batteries are reliable, efficient, and have a longer lifespan, lead-acid batteries are less expensive upfront [30]. One study optimized energy storage and compared vanadium redox, zinc bromine, and sodium sulfur, as well as lithium ion-and lead-acid batteries. In this study, the authors noted that lithium-ion is the most energy dense and most efficient battery storage compared. One study directly compared lithium-ion and lead-acid and found that lithium-ion batteries yield a lower cost throughout the life of a microgrid because of their long lifespan. Researching a system using cheaper batteries would provide important knowledge that could be useful for an area that is trying to have a low overall microgrid cost. Another author researched a system using a lithium nickel manganese cobalt oxide battery, which is essentially a more efficient, dependable, and safe lithium-ion battery [31]. Two publications in this review had microgrids without energy storage, as these were connected to the utility grid and thus needed no energy storage. Research was also conducted on a microgrid using a fuel cell, which is similar to a battery but do not need to be recharged and uses hydrogen for energy [32]. Storing energy in a microgrid is critical, as unstored energy is wasted and would ultimately increase the cost of a microgrid system.

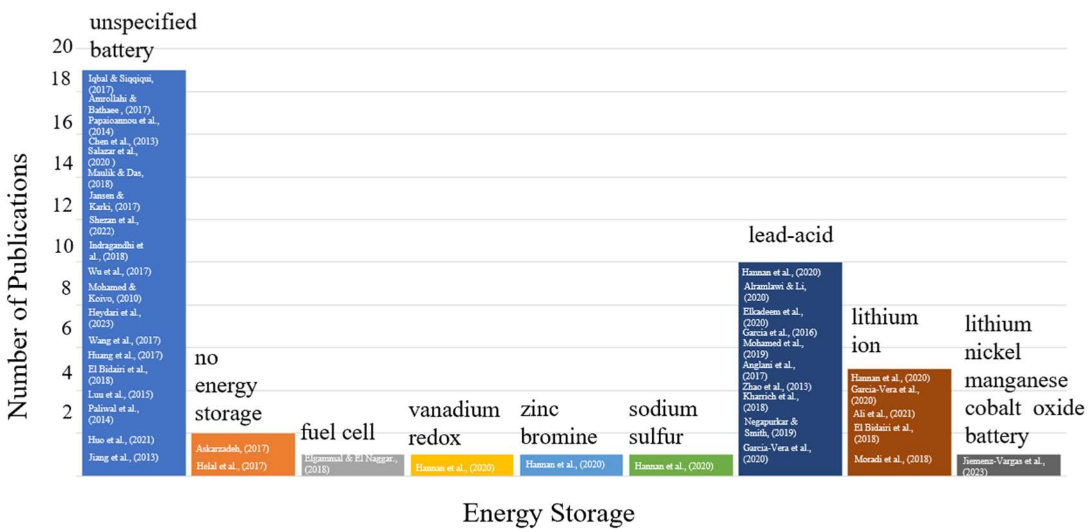

Figure 4: Types of Energy Storage Included in Microgrid

Optimization Objectives

The optimization objectives were the primary focus of this review. Environmental, economic, and technical objectives were the three main categorizations, as shown in Figure 5, and input variables for each study are included in Appendix A. The economic objective category has the widest range of optimization objectives, as well as the largest number of publications, suggesting that cost was a key consideration for most researchers. Minimizing operation and maintenance costs is the most common objective among publications. The next most common objective is to minimize carbon emissions, followed by minimizing Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and the production of fossil fuels.

Most authors shared an interest in the economic benefits of microgrids. Over half of authors chose to focus on minimizing operation and maintenance costs. Without operation and maintenance, a microgrid cannot function, but it could be a deterrent if an area cannot afford to upkeep a microgrid system. NPC is "the present value of all the costs of installing and operating the [c]component over the project lifetime, minus the present value of all the revenues that it earns over the project lifetime [33]." On the other hand, LCOE is the net present cost related to energy production. Levelized cost of energy "[a]llows the comparison of different technologies (e.g., wind, solar, natural gas) of unequal life spans, project size, different capital cost, risk, return, and capacities [34]." If the NPC and LCOE are low enough, a community may have more of an incentive to implement a renewable hybrid microgrid. Some authors chose to study the economic benefits of parts of the microgrid life cycle, which provide less information about overall microgrid cost than NPC or LCOE.

Environmental costs and benefits were also studied by a majority of authors, though there are less publications with environmental objectives than that of the economic objective category. Minimizing carbon emissions was the most common environmental objective, followed by minimizing the utilization of fossil fuels, and lastly maximizing the use of renewable energy sources. There are many countries with goals of minimizing environmental impacts, which is why it was an objective of many authors. Of the 17 goals of sustainable development put forth by the United Nations, affordable and clean energy is goal #7, sustainable cities and communities is #11, and climate action is #13 [35]. Though economic cost was a common objective of most authors, it was usually paired in a multi-objective function, since there is a global emphasis placed on preventing climate change.

Very few authors chose to study technical objectives. Minimizing power losses was a focus for three research teams, because delivering reliable power is critical, but may be challenging, in a renewable microgrid. Maximizing system lifespan is an important consideration, as a longer lifespan could mean less overall economic and environmental costs. It is interesting that there is only one paper concerned with maximizing energy storage, because energy that cannot be stored will be wasted, which can also impact economic costs.

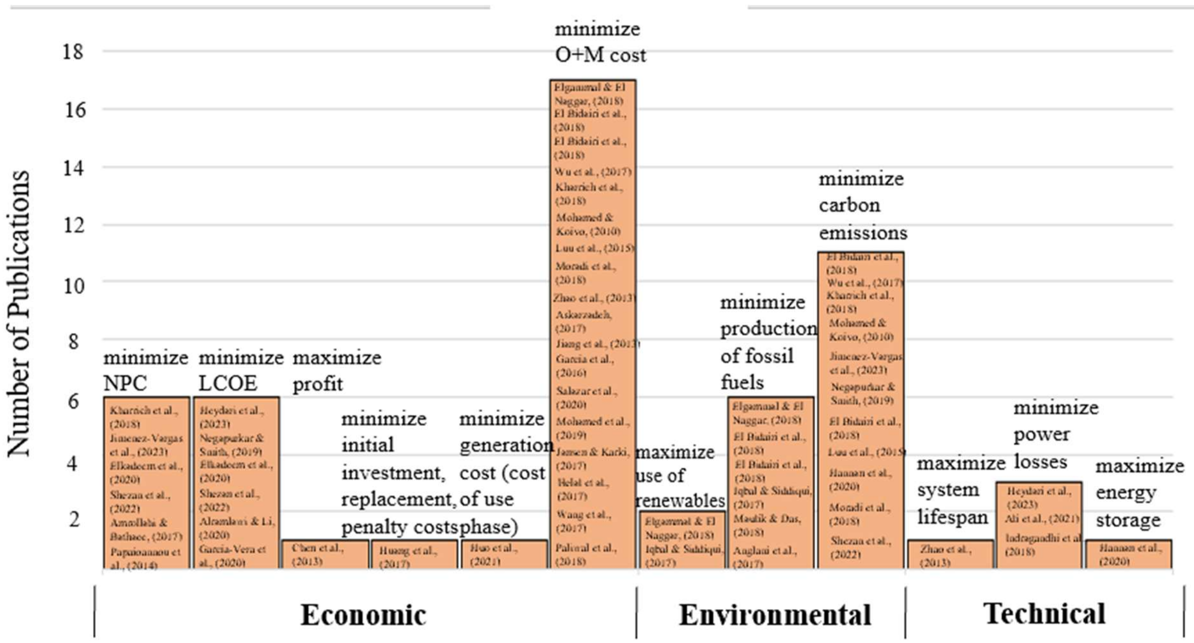

Figure 5: Optimization Objectives of Both Single and Multiobjective Studies

While Figure 5 is only showing the type of objectives, Figure 6 shows the amount of single or multi-objective publications within the scope of this review. Most single objective studies strove to minimize cost and were more common. Environmental objectives were considered when paired with economics in multiobjective studies. Single objective studies were more common, but multiobjective studies are important because they study the trade-offs of two or more objectives which is valuable information for someone like a stakeholder.

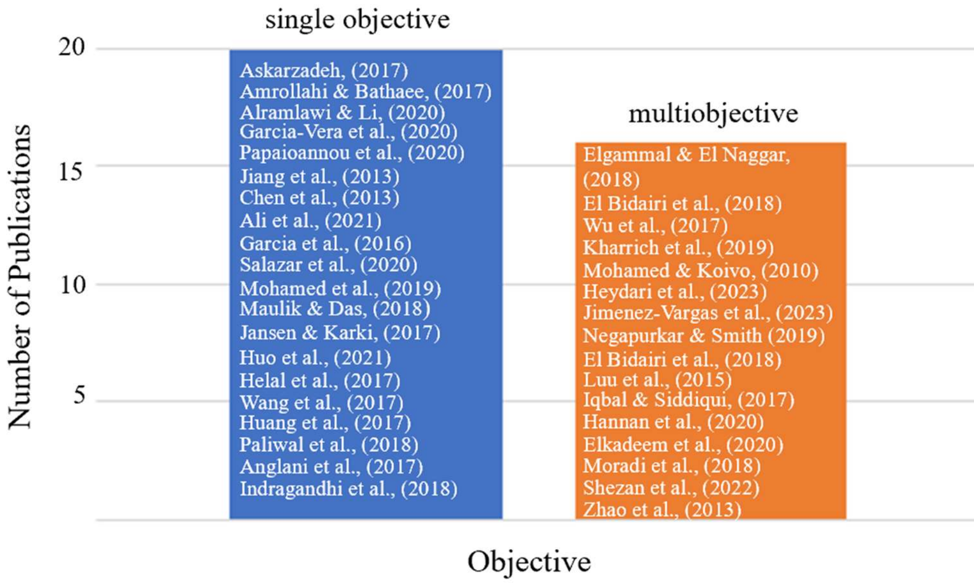

Figure 6: Type of Publication Objective

Major Findings

There were some interesting findings that arose during this literature analysis. There are benefits and drawbacks to using each type of renewable energy resource, which makes it challenging to identify which of solar, wind, ocean, or bioenergy is the best option for lowest environmental and economic costs. Most publications are cost-focused, and if they are multiobjective, they are likely paired with an environmental objective. Though reducing carbon emissions and encouraging the use of renewable energy are global goals set forth by the UN, ultimately, the optimal microgrid solution is up to stakeholders and buyers.

It is compelling that Europe is the second highest leader in microgrid research according to this study. While I initially believed Europe’s main reasoning for investing in microgrid research was for climate benefits only, and I was surprised to learn that Europe’s utility grid is not always reliable and has previously caused blackouts in the United Kingdom. It was also striking that North America has the least interest in microgrid research within this literature study, though large investments may change this in the coming years. It was unsurprising that Asia is currently the pioneer in microgrid research because of the many islands of Southeast Asia that need reliable power.

Based on the gaps found in this analysis, future research into renewable hybrid microgrids should consider using inflow-hydrokinetic technology because of its low ecological harm and passive nature. Of the optimization objectives collected, it is worth noting that there were no social objectives considered in this study, such as providing more people with power or investigating how microgrid implementation could physically impact a community.

Ultimately, knowledge of hybrid microgrids is growing as research increases. Microgrids are extremely desirable in islanded places, as well as areas targeted by severe weather. The future may look like a world so populated with microgrids that there may not be a need for a utility grid at all. The stability and reliability that renewable based hybrid microgrids can provide makes them a solution capable of maintaining infrastructure and public safety against the imminent threat of climate change.

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Appendix

Appendix A: Input Variables Manipulated for Optimization Objectives

Author	Input Variables
Faisal et al., (2018)	comparing different types of energy storage
Elgammal and El-Naggar, (2018)	weather and demand patterns
Askarzadeh, (2017)	generation pattern of wind turbines, PV panels, combined heat and power
Iqbal and Siddiqui, (2017)	microgrid topology (power sources, energy storage, loads)
Amrollahi and Bathaee, (2017)	weather pattern, demand pattern, specs and economic parameters of components
Alramlawi and Li, (2020)	cost of system components
Garcia-Vera et al., (2020)	various battery models and technologies
Papaioannou et al., (2014)	different capacities of PV panel, batteries, inverters, and charger
Hannan et al., (2020)	energy storage system sizing
Jiang et al., (2013)	technical specifications (power of controllable units, DS bus voltage)
Elkadeem et al., (2020)	various configurations of a hybrid renewable energy based microgrid
Chen et al., (2013)	component sizing (energy storage, panel size)
Moradi et al., (2018)	with or without access to battery storage
Ali et al., (2021)	different scenarios: PEV parking lot location, historical load, solar irradiance, wind speed data, size of PV/WT
Garcia et al., (2016)	lifetime estimations calculated hourly for two different energy storage systems
Salazar et al., (2020)	scheduling battery charge/discharge in nanogrid supplied by both traditional and renewable sources
Mohamed et al., (2019)	microgrid operating scenarios (AC/DC converters with varying sizes allocated within the microgrid) and equipment sizing
Maulik and Das, (2018)	power output
Jansen and Karki, (2017)	pv sizing and battery capacity
Shezan et al., (2022)	different scheduling scenarios
Anglani et al., (2017)	sizing of battery energy storage system
Zhao et al., (2013)	lifetime characteristics of lead-acid batteries
Indragandhi et al., (2018)	sizing of renewable energy sources PV, battery, wind systems
El Bidairi et al., (2018)	scheduling of energy sources (renewable and diesel)
Wu et al., (2017)	(varying investment costs of Pv modeules, ocean energy generating devices, diesel engines, and energy stoage modules, varying the power output of disel engines
Kharrich et al., (2018)	size of pv and wind generation
Mohamed and Koivo, (2019)	3 operational scenarios
Heydari et al., (2023)	different demand scenarios for different sizes of communities
Jiménez-Vargas et al., (2023)	power generated from different energy sources
Negapurkar and Smith, (2019)	number of pv module, wind turbine, lead-acid battery, biodeisel generator, fuel cell, electrolyzer, H2 tank
Huo et al., (2021)	microgrid dispatch rule base (when to let each of the generators generate, or how priority is decided- meeting demand or charging the battery)
Helal et al., (2017)	scheduing of energy sources
Wang et al., (2017)	active power of each microgrid source (dispatch, how much power should one source generate)
Huang et al., (2017)	scheduling of energy resources
EI Bidairi et al., (2018)	battery storage size
Luu et al., (2015)	scheduling energy resource distribution
Paliwal et al., (2018)	energy generation and demand scenarios (wind turbine generation, PV generation, etc)