Microgrids for Energy Transition

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Contributor: Jae-Hyup Lee

International, national, and subnational laws and policies call for rapidly decarbonizing energy systems around the globe. This effort relies heavily on renewable electricity and calls for a transition that is: (i) *flexible* enough to accommodate existing and new electricity end uses and users; (ii) *resilient* in response to climate change and other threats to electricity infrastructure; (iii) *cost-effective* in comparison to alternatives; and (iv) *just* in the face of energy systems that are often the result of—or the cause of—procedural, distributive, and historical injustices. Acknowledging the intertwined roles of technology and policy, this entry provides a cross-disciplinary review of how microgrids may contribute to renewable electricity systems that are flexible, resilient, cost-effective, and just (including illustrative examples from Korea, California, New York, the European Union, and elsewhere).

Keywords: microgrid ; renewable ; renewable portfolio standard ; 100% ; resilience ; energy justice ; tariff ; climate change ; Hawai‘i ; Puerto Rico

1. Introduction

The climate crisis calls for rapidly transforming the global energy system. As described by the Intergovernmental Panel on Climate Change (IPCC), model pathways for limiting global warming to 1.5 °C indicate that global net anthropogenic carbon emissions will need to decline by about 45% from 2010 levels in the next decade, and reach net zero by around 2050 [1]. Much of these emissions reductions must come from the energy sector, with a particular focus on electricity. The IPCC's successful model pathways are characterized by energy demand reductions, decarbonization of energy systems, and electrification of energy end uses such as transportation and heating. Professor Leah Stokes has thus framed the situation this way: “The pace and scale of cleaning up the electricity system are not secondary issues but the central challenge” [2].

At the same time, in the interest of sustainable development, the world has committed itself to universal access to “affordable, reliable, sustainable and modern energy” [3]. This type of universal access will require that decarbonized energy systems deploy near-universal modularity and flexibility, accounting for both existing and new energy users and uses. C. Baird Brown, who in the role of an attorney for energy consumers and communities must account for this diversity at the grid edge, has observed that the “challenge of meeting the decarbonization goals is not simply a problem of installed MW of capacity. The challenge is to build a decarbonized system that works as a system to meet customer needs” [4].

However, even this framing does not capture the full complexity of the transition. A variety of scholars, advocates, and policymakers have called for a deeper transition, which fundamentally recasts energy systems in ways that address energy injustices via procedural justice, distributive justice, and restorative justice [5]. All the while, the harsh reality of the climate crisis reminds us that modern energy systems must also become more resilient and adaptive to climate change, even as they transform to mitigate its severity.

Plainly, this transformation is no small task. Perhaps it is counterintuitive that small-scale energy systems might play a large-scale role in defining this modern energy transformation. Consider the microgrid, which is defined by the U.S. Department of Energy as “a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode” [6].

Acknowledging the intertwined roles of technology and policy, this review reflects upon the role of microgrids in the transition to 100% renewable energy, considering how they can contribute to a flexible, resilient, cost-effective, and just electricity system. After providing a cross-disciplinary review of generalized microgrids characteristics relevant to this transition, we consider the role and potential of microgrids in the context of regulated electric utilities in two United States jurisdictions with 100% renewable energy standards, Hawai‘i and Puerto Rico. Both jurisdictions are actively developing microgrid regulatory structures.

2. Generalized Microgrid Characteristics and Potential

Framing the emergence of microgrids “as a flexible architecture for deploying distributed energy resources (DERs) that can meet the wide ranging needs of different communities from metropolitan New York to rural India,” Hirsch et al.’s excellent review of microgrids identified three characteristics driving microgrid development in locations with existing grid architecture: energy security, economic benefits, and clean energy integration [7]. While we concur that these are important drivers, we choose to categorize general renewable microgrid characteristics slightly differently—in the hope of capturing a panoply of potential microgrid attributes most relevant to the renewable electricity transition. These potential attributes include the ability to improve upon the flexibility, resilience, cost-effectiveness, and fairness of a decarbonized electricity system.

2.1. Flexibility and Modularity

The potential flexibility of microgrids is often explained via their potential application to a variety of on-grid or off-grid use cases. These include examples such as electrifying remote or underserved communities, serving critical loads, and developing campus microgrids. However, flexibility characterized solely by end use paints an incomplete picture of microgrid potential.

2.1.1. Modular Grid Planning

Van Nostrand noted that in the grid-connected context, microgrids can offer an alternative to typical electric utility investments and grid planning:

Because the optimal size for additions of nuclear, coal, and natural gas-fired generating stations under the traditional utility-scale central generating station model is fairly large, investments by utilities in new generating capacity are said to be ‘lumpy,’ or available only on a substantial scale. This large scale contrasts sharply with the more steady and smooth growth in demand typically experienced by retail electric utilities. As a result, the resource additions under the traditional utility-scale model often result in a short-term mismatch between loads and resources [8].

This mismatch between resource additions or subtractions, in comparison to growing or shrinking load, can also lead to other imbalances, such as between investments by a regulated utility and charges passed along to consumers under the “used and useful” standard commonly used by regulators to evaluate utility investments [8]. Unless traditional large-scale fossil fuel-fired resources are replaced by decarbonized resources on a uniformly 1:1 basis, the same mismatches can be expected during the forthcoming energy transition.

Moreover, the problem of lumpy investment and deployment is not limited to generation resource additions; transmission capacity is emerging as a key barrier to deploying large-scale renewable energy projects. In the United States, for example, some have identified a need for significant new transmission infrastructure in order to connect coastal population centers with wind resources that are concentrated in faraway Midwest and Plains states [9]. Related proposals, such as a “North American Supergrid,” face barriers to deployment, including potential (i) opposition from communities asked to host transmission infrastructure without directly benefitting from the energy it carries, (ii) trans-jurisdictional wrangling between state governments and the federal government, and (iii) controversial decisions about ownership and eminent domain [10]. These questions about new transmission capacity questions are not unique to the United States. For example, a “Northeast Asian Super Grid” concept would create transmission links between the grids of China, Mongolia, Japan, Korea, and possibly Russia, perhaps in conjunction with large-scale renewable energy production in the Gobi Desert [11][12]. A European “megagrid” concept similarly seeks to take advantage of geographic diversity with a European Union-wide interregional sharing of large-scale renewable generation, involving several thousand kilometers of new interregional transmission capacity [13]. Much like in the United States’ example, one can envision substantial jurisdictional hurdles for these transmission-heavy concepts, particularly in relation to international borders such as between North Korea and South Korea.

Microgrids and other forms of distributed infrastructure present a flexible alternative, to offset some of the need to expand the grid via new large-scale generation and transmission capacity. Microgrids can deploy distributed generation, load management, and/or ancillary grid services in more modular quantities, nearer to load, and in response to the marginal needs of a grid operator. Moreover, scaling generation to directly match the needs of customers can reduce contingencies and the resulting need for grid-scale reserves [4]. "Reducing demand—both in the long term and by shifting load away from peak—can have the same effects" [4]. Microgrids may enhance this type of demand management, by fostering a network effect and aggregation opportunities among participants.

2.1.2. Flexibility and Decarbonization

With respect to their wide range of potential topologies and end uses, the flexibility of renewable microgrids creates at least one challenge for the task of evaluating their role in a decarbonized electricity system: what is the emissions impact of a microgrid? Certainly, the emissions impact of specific technologies can be evaluated utilizing lifecycle analyses. To the extent that renewable microgrid generation resources displace fossil fuel-powered generation, the resulting lifecycle emissions reductions can be substantial [14][15][16][17]. However, microgrids conforming to the U.S. Department of Energy definition (i.e., those that can island from the grid) are also likely to incorporate energy storage systems. Here, the lifecycle emissions associated with manufacturing, transportation, and installation of storage technologies must be considered alongside operational characteristics. These might include questions about: how the storage is deployed (e.g., is it utilized during day-to-day operation, or solely as a backup resource in islanded mode?); how it is charged (e.g., from renewable generation, or from fossil fuel-fired generation?); whether the use of stored energy creates significant round-trip inefficiencies associated with charging and discharging; and the lifetime of a particular energy storage technology [18].

Perhaps due to the complexity of these questions, microgrids have been the subject of relatively few studies on lifecycle emissions, focused largely on solar-powered remote microgrids [19][20][21][22]. These studies generally conclude that such microgrids "cause significantly less climate change impacts compared to other electricity generation technologies" [19]. Papageorgiou et al. extended this type of lifecycle analysis to a grid-connected battery-backed microgrid in Sweden [19]. Reinforcing the complexity described above, their results indicate that the emissions impact of a microgrid is highly dependent on the marginal source of electricity in the absence of the microgrid. Thus, they conclude that solar microgrids can contribute to decarbonization in areas where the carbon intensity of other generation resources is high, but not in areas with an abundance of low-carbon resources. This observation is highly relevant in the context of considering 100% renewable energy systems, where one may assume that alternative marginal resources will—eventually—consist solely of relatively low-carbon renewables.

However, the marginal resources evaluated by Papageorgiou et al. did not include grid-based storage resources. It is safe to assume that many or most 100% renewable electricity systems will incorporate grid-based storage. Raugei et al. quantified the lifecycle emissions associated with adding lithium-ion batteries to a ground-mounted grid-based photovoltaic system under several storage configurations and battery chemistries, and compared the results to fossil-fuel fired generation [23]. They concluded that "broadly speaking, results for all conventional thermal generation invariably indicate over one order of magnitude higher greenhouse gas emissions…generation with respect to all [photovoltaic] systems, regardless of the amount of storage" or the type of battery. Although further research is warranted to evaluate the lifecycle emissions under a wide range of microgrid topologies and operational modes, this result suggests that storage-backed microgrids can indeed play a role in decarbonization.

2.2. Resilience

Early microgrids were not developed as a tool for climate mitigation, but rather as a tool for increasing resilience to various vulnerabilities. For example, medical facilities, military facilities, and other energy consumers seeking enhanced resilience have long utilized microgrid architectures to host emergency generating capacity, such as diesel generators [7][24][25]. More modern microgrids can retain this resilience while also deploying decarbonized renewable generation paired with local energy storage. To the extent that climate adaptation involves, in part, increasing the resilience of electricity infrastructure, this dual deployment of climate mitigation capacity and climate adaptation capacity is the recipe invoked by the IPCC and others: "Climate change has started to disrupt electricity generation and, if climate change adaptation options are not considered, it is predicted that these disruptions will be lengthier and more frequent. Adaptation would both secure vulnerable infrastructure and ensure the necessary generation capacity" [8][26][27][28].

2.2.1. Physical Resilience

2012′s "Superstorm" Sandy illustrates the potential resilience capacity of microgrids [8]. An unprecedented fourteen-foot storm surge swamped grid infrastructure across population centers in the eastern United States, leaving more than eight million utility customers without power—some for weeks. After scrambling to replace thousands of utility poles, thousands of transformers, and hundreds of miles of cable, utilities in the region sought billions of dollars in customer rate increases to apply storm-hardening measures to the grid. In response, a variety of non-governmental organizations and experts advocated for a more deliberate evaluation of the role of microgrids and distributed generation in adding resilience to the region's electricity grid. They noted that many educational institutions, housing communities, hospitals, data centers, and other facilities hosting island-able distributed generation were able to maintain power during the storm's disruptions.

Despite its "Superstorm" tagline, Sandy was not an isolated incident. 2020's Tropical Storm Isaias led to outages for 900,000 New York utility customers [29]. After an investigation of several utilities' storm response, New York's utility regulator (the New York Public Service Commissions, NYPSC) noted that "more so than any previous time, New Yorkers are depending on essential electric services as a foundation for managing their lives during the ongoing global coronavirus pandemic" [30]. In an order requiring several utilities to show cause why the NYPSC should not seek court-imposed or administrative penalties against the utilities, the commission asserted that "the dramatic and lengthy electric service failure that [NYPSC] Staff observed as a result of [Tropical Storm] Isaias suggested that some electric service providers did not fully appreciate the basic need for safe and reliable electric service." Among other apparent violations, the commission identified failures to contact some "life support" customers (those who require electrically operated machinery to sustain basic life functions), and refer them to emergency responders. "Recognizing prior instances where [the utilities'] storm response had fallen short of legal requirements," the commission noted that if it classified these infractions as repeated violations, the commission would commence a proceeding to revoke or modify the utilities' authorization to operate. This extraordinary potential legal remedy reflects the importance—sometimes life-sustaining importance [31]—of electric grid resilience.

On the other side of the United States, California's grid experienced another form of natural disaster, via wildfires intensified by climate change [32] and, in several notable cases, caused by grid infrastructure [33]. In June 2020, California's Public Utilities Commission adopted short-term actions intended to accelerate the interconnection of microgrids and other "resiliency projects" in advance of the upcoming wildfire season [34]. This order required the state's large investor-owned utilities to "(a) develop and implement standardized, pre-approved system designs for interconnection of resiliency projects that deliver energy services during grid outages; (b) develop and implement methods to increase simplicity and transparency of the processes by which the utilities inspect and approve a project; and (c) prioritize interconnection of resiliency projects for key locations, facilities, and/or customers." The decision also modified net energy metering (NEM) tariffs to allow storage devices to charge from the grid in advance of wildfire threats, and to remove size limits for NEM-paired storage projects.

A microgrid-focused response like California's is supported by technical and theoretical analyses of the microgrids impacts on grid fragility, survivability, and recovery [26]. Liu et al., for example, concluded that "microgrids represent a key component in power grid for improving the grid resilience" (with the caveat that additional work is needed to evaluate the sensitivity of grid resilience on the number of microgrids operating on a system) [35]. Hussain et al. noted other studies evaluating how microgrids can add resilience as a local resource, a community resource, and/or a black-start resource for the wider grid [36]. Syrri et al. provided a framework for assessing the reliability impacts of grid-connected microgrids, concluding that microgrids can offer reliability benefits to microgrid participants and to energy consumers on the wider grid [37][38]. Illustrating the multifaceted potential for microgrid resilience attributes, Strbac et al. described how microgrids might even play a role in increasing the resilience of the European megagrid concept described above [13].

2.2.2. Digital Resilience

Of course, natural disasters are not the electric grid's only vulnerability. Cyber security, for example, is an increasing concern for all infrastructure in the digital age, including microgrids [39][40]. Qi et al. noted that the "threat of cyber-based attacks targeting the…energy sector, and in particular the electric power grid, is growing in number and sophistication" [41]. They (and others) have proposed a multilayered framework for modeling, preventing, detecting, and responding to cyber threats, in response to the concern that increasing penetration of distributed energy resources will result in a proliferation of devices and access points outside a utility's direct administration and thus expand the vulnerable "attack surface." It is not clear, however, that distributed resources nested within networked microgrids are inherently more vulnerable to cyber threats than existing centralized grid architectures. This is especially apparent when one considers the traditional role of microgrids that were developed especially to serve critical loads in the face of these types of vulnerabilities. Veitch et al., for example, described a microgrid security architecture for military microgrids in the United States that segments control systems based on functional necessities, physical locations, and/or security concerns [42]. They asserted that this type of isolation can minimize malicious opportunities, provide good locations for intrusion detection, and improve network performance. This approach appears to operationalize the type of potential microgrid security benefits described by Qazi and Young, who postulated that solar-based microgrids are less vulnerable to cyberattacks because of their ability to island from the main grid [43].

2.3. Cost-Effectiveness

2.3.1. Levelized Cost of Energy

The narrative of inherently "expensive renewables" is eroding. For example, asset management and financial advisory firm Lazard's most recent study of the levelized cost of energy (LCOE) reported that the unsubsidized cost of new utility-scale wind and solar generation is generally lower than the cost of new fossil fuel-fired generation—particularly when accounting for the sensitivity of fossil fuel-fired generation to fuel prices [44]. Lazard noted, of course, that LCOE does not allow for a fully direct comparison between all types of generation, as it does not account for potential social and environmental costs, geographic distribution, dispatch characteristics, or reliability-related considerations. Nonetheless, the LCOE analysis does illustrate the trend that decreasing capital costs, improving technologies, and increased competition, among other factors, are driving down the price of renewables. Moreover, Lazard reported that combining distributed solar generation with energy storage at the microgrid scale (i.e., residential, or commercial and industrial applications) results in a lower levelized cost of storage compared to standalone storage at the same scale.

Microgrids and microgrid-scale storage can also contribute other energy services and functions, such as demand response capacity, frequency regulation, resource adequacy, spinning reserve, and backup power during grid outages [45][46]. Value streams like this, previously largely served by fossil fuel-fired generation, are key components of 100% renewable electricity systems. Thus, while Lazard and others report that levelized costs of renewables at the microgrid scale are presently higher than costs at larger scales, it appears possible that microgrid-scale renewables may be able to capture a variety of these other potential value streams, while continuing to benefit from the same factors driving down costs at other scales (e.g., improving technologies and increased competition).

2.3.2. Considerations beyond Levelized Cost of Energy

Various authors have identified the types of costs and benefits that can help to define this broader view of microgrid cost-effectiveness. Brown asserted that with an appropriate methodology to value grid-edge resources, "microgrids employing multiple energy management technologies can simultaneously provide multiple dynamic objective functions" [4]. These include the ability to adjust generation and load, to shape an aggregate profile, to shift load, and to locate generation closer to load—strategies that can help moderate power prices and manage grid congestion [4]. Resilience is another relevant value stream. Anderson et al. concluded that monetizing the resilience value of renewable energy systems at the building and campus scale (i.e., relevant to microgrids) is a multi-billion-dollar opportunity in comparison to existing energy backup systems [47]. These concepts reinforce the idea that traditional notions of cost-effectiveness (e.g., LCOE) do not capture all relevant costs and benefits relevant to the current electricity transformation. Table 1 identifies some of the cost-effectiveness considerations that may be particularly relevant to microgrids. However, utility business and regulatory models have not yet resolved how to monetize all of these costs and benefits. For example, it remains challenging to value resilience in the context of evaluating the prudence of proposed grid-hardening investments [48][49][50].

Table 1. Some cost-effectiveness considerations relevant to microgrid policy.

Potential Benefits	**• Generation capacity and resource adequacy • Energy storage capacity • Demand response capacity and load-shaping • Frequency regulation • Spinning reserve • Backup power during outages • Transmission infrastructure mitigation • Resilience • Efficiency • Load diversity**
Potential Costs	**• Levelized cost of infrastructure, operation, and maintenance • Transmission and distribution losses • Land use and energy sprawl • Grid hardening investments • Social cost of carbon, and other environmental costs • Cybersecurity infrastructure and monitoring • Transaction costs associated with recruiting microgrid participants, grid interconnection, etc. • Energy storage round-trip losses • Energy monitoring and communication infrastructure**

Cost-effectiveness also invokes comparison to alternatives. In the current energy transition, those comparisons must go beyond the fossil fuel generating resources identified in Lazard's LCOE analysis. Larsen et al. noted that storm hardening of existing grid infrastructure would cost trillions of dollars [51]. This is relevant to assessing the cost-effectiveness of microgrids if they contribute to physical resilience. A robust view of energy costs in the context of the climate crisis should also explicitly consider the cost of carbon sequestration or other mitigation strategies for GHG-emitting alternatives. Related to the potentially troublesome task of combining large-scale renewable generation with large-scale transmission infrastructure, Bronin argued that the resulting “energy sprawl costs space, money, and energy itself” [52]. These costs are related to the balance of costs and benefits in existing land uses and land-use policies, the expensive need to coordinate across jurisdictional and ownership boundaries, and the energy losses associated with transmission.

Polly et al. and Saleski et al. evaluated the potential cost-effectiveness of zero-energy districts [53][54]. These are conceptualized as parts of cities designed to balance energy consumption and generation, via district energy systems that coordinate energy generation and demand, energy storage, and waste heat, etc., across multiple buildings. Compared to standalone net-zero energy buildings, these urban districts may be able to improve energy cost-effectiveness by leveraging characteristics such as load diversity, scale, and coordinated participation in markets for ancillary grid services [53][54]. This is particularly relevant, because (i) governments are implementing net-zero energy building standards for new or rebuilt buildings, (ii) population is shifting to urban areas, (iii) buildings account for nearly 40% of energy-related GHG emissions, (iv) the growth in building floor area is outpacing population growth [55][56][57]. Microgrids—like zero-energy districts—can also coordinate generation and load, and may also enjoy other similar characteristics such as load diversity and coordinated participation in markets for ancillary services. Thus, it seems worthy for future research to explore the role of microgrids in urban zero-energy districts, and to further quantify the cost-effectiveness benefits of these coordinated systems.

The above examples illustrate the tangled role of technology and policy in evaluating the cost-effectiveness of various components in the energy transformation. Microgrids are likely to play a substantial role in a decarbonized energy system only if mechanisms such as electricity tariffs (applicable to the provision and consumption of energy and energy services by microgrids), prudence reviews of utility investments, building standards, and land-use policies are able to assess or define the value of microgrid characteristics. Hatziargyriou et al., quantifying the economic, environmental, and operational benefits of microgrid penetration in Greek networks, similarly argued that “microgrids will only mature as a viable market alternative for consumers and utilities when all the benefits provided by a particular microgrid are accounted for and credited to its owners” [58]. Yet the characteristics (and resulting benefits and costs) of a microgrid are, at least in part, dependent on the technology mix incorporated into the microgrid. In turn, communities and broader energy systems are only likely to invest in a technology if it appears that the value outweighs the costs.

While prior works acknowledge this interdependency between policy and technology, the transition to 100% renewable energy prompts re-evaluation. For example, a thorough review of microgrid economics by Milis et al. concluded that “where the most often viable reported system configuration is concerned, the current scientific consensus is that [combined heat and power]-powered microgrids are the most economically viable type of microgrid under a wide range of policy interventions, with renewable powered microgrids only viable in fringe cases, making the often-heard claim that microgrids will allow for greater penetration of renewable sources highly suspect at best” [59]. In the context of the growing number of jurisdictions planning for 100% renewable electricity systems, this “fringe case” is the norm, yet that scenario is the subject of only one study reviewed by Milis et al. Accordingly, the review acknowledged that “a lot of research attention has been devoted to the topics of carbon taxation and TOU-tariffs,” with “other subjects such as tax incentives or command and control policies only receiving moderate research attention.” Furthermore, “concerning the objective of outlining any research gaps, [the review showed] that the exploration of the impact of tariff systems other than TOU-pricing on the optimal configuration of a microgrid hasn’t received research attention.” In addition, the economic impact of other important policy-influenced microgrid characteristics, such as infrastructure scale, location, and effects on land use, should also be accounted for. An even broader socio–techno–economic analysis, including these elements and more (e.g., the impact on jobs), will also be required to account for how policy and technology decisions are succeeding or failing to promote energy justice (discussed below).

Gaps in the evaluation of microgrid cost-effectiveness appear to be long-lived. Discussing policy-making for microgrids in 2008, Marnay et al. noted that “microgrids bring to the fore the issues of waste-heat-driven cooling, on-site energy storage, and heterogeneous [power quality and reliability], which [were] all relatively uncharted areas of engineering-economic analysis” [60]. It appears that, perhaps as much as any other potential component of 100% renewable energy systems, microgrids suffer from a “chicken or egg” problem in the realm of assessing cost-effectiveness in the midst of co-evolving policies and technologies. This suggests that an analysis of the economic impacts of microgrids in 100% renewable energy systems, considering a wide range of potential characteristics, costs, and benefits, is a useful area for further inquiry.

Remote and island microgrids may provide fertile ground for this line of inquiry. For example, Gasa Island and Gapa Island in the Republic of Korea are each the site of microgrids that incorporate renewable generating capacity. Gapa’s microgrid was developed with two wind turbines (250 kW) and almost fifty solar panels (174 kW total), supplemented by a

3.85 MWh battery system and diesel generators [61][62][63][64]. The subsequent renewable component of the islands electricity has reportedly ranged from approximately 40% to 80%, and as of 2018, the island could self-sustain for seven days. With the battery capacity doubled, this mode of operation is expected to last up to 25 days. In the meanwhile, the microgrid project has been associated with a substantial decrease in local energy costs. Before the project, the average monthly electricity bill of each household on Gasa was around 120,000 to 130,000 won; this reportedly dropped to approximately 20,000–25,000 won with the microgrid project [63].

Similar results have been reported for a microgrid project on Gasa Island, serving approximately 165 households, lighthouses, waterworks, and military radar facilities. This microgrid utilizes four 100 kW wind turbines, four photovoltaic installations totaling approximately 320 kW, and three diesel power units totaling 450 kW [62][65]. Excess energy is stored in a 3 MWh battery system, which enables full-day electricity consumption throughout the whole island if fully charged [66]. After installation, the consumption of diesel dropped substantially [67], and Kim and Mathews reported a 200 won/kWh savings compared to diesel generation [65]. It would be interesting for future research to explore how the reported savings on Gasa and Gapa relate to the levelized cost of energy, and how broader treatment of costs and benefits might be compared to the scale of the reported savings.

Korean islands have long been identified as prime candidates for microgrids [68], and may be particularly useful sites to study these cost-effectiveness issues in the context of 100% renewable energy standards. The Jeju province, home to Korea's largest and most populated island (and also home to the much-smaller island of Gapa), adopted a 100% renewable energy target (2030) in 2012 [69], making it one of the earliest jurisdictions to adopt such a policy. This initiative was expected to act as an important reference source for South Korea's broader energy transition, creating a test bed for modern grid technology [65]. With the 2020 adoption of a South Korean Green New Deal policy targeting carbon neutrality for the entire country by 2050, this test bed will naturally inform Korean decarbonization efforts beyond remote island settings [70]. Indeed, Korea has already developed microgrids in a number of urban settings [61]. Similarly, Hawai'i and Puerto Rico (discussed below) have each adopted 100% renewable electricity standards, and both jurisdictions include a mix of remote island settings and urban areas. This makes them suitable locales to investigate the role of renewable microgrids.

2.4. Energy Justice

2.4.1. Examples of Energy Justice Principles Embedded in Policy

International, national, and subnational policies have called for the renewable energy transition to incorporate justice [71]. The Paris Agreement, for example, incorporates justice principles that are applicable at the international and national scale: "[The Parties will implement the Agreement] to reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances" [72]. The Agreement also references justice principles more applicable at community scales, claiming to account for "the imperative of a just transition of the workforce and the creation of decent work and quality jobs in accordance with nationally defined development priorities." It also acknowledges that climate action should "respect, promote and consider their respective obligations on human rights, the right to health, the rights of indigenous peoples, local communities, migrants, children, persons with disabilities and people in vulnerable situations and the right to development, as well as gender equality, empowerment of women and intergenerational equity." With these words, the Agreement "became the first multilateral environmental agreement to contain an explicit reference to human rights, albeit in its preamble" [73].

Recent European Union (EU) policy-making also provides an example of energy justice-relevant policy. The 2019 EU electricity market directive includes a variety of provisions related to small consumers in liberalized European energy markets, with a general approach self-described as "competitive, consumer-centred, flexible and non-discriminatory" [74]. (Here, the phrase "non-discriminatory" appears to be largely focused on avoiding barriers to market entry, and avoiding cross-participant subsidization, rather than non-discriminatory in other senses of the phrase.) Among other provisions, the directive provides for "citizen energy communities" to participate in energy markets. These are legal entities: (a) that "are based on voluntary and open participation and is effectively controlled by members or shareholders that are natural persons, local authorities, including municipalities, or small enterprises;" (b) whose "primary purpose [is] to provide environmental, economic or social community benefits to its members or shareholders or to the local areas where it operates rather than to generate financial profits;" and (c) who "may engage in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services or charging services for electric vehicles or provide other energy services to its members or shareholders." Although it remains unclear exactly how these communities will participate in various energy markets, Mostert and Naude asserted that this concept has a bearing on energy self-sufficiency: "The implication of this provision may be that more traditional energy supply companies have to lower their prices if they wish to discourage such local communities from generating their own electricity" [75]. Roggenkamp and Diestelmeier also discussed the extent to which the EU directive may influence energy justice within member states, with a particular focus on how provisions related to energy poverty and the protection of small electricity customers are translated into the energy policy of member states [76]. They described that, although the directive recognized a role for enhanced participation by consumers (i.e., prosumers), uncertainty and disparity remain across member states in terms of defining vulnerable classes of customers and consumer protections could. They cautioned that this could result in a two classes of prosumers: "one which is able to 'take ownership of and benefit from new technologies' and another category which is not able to do so and remains vulnerable to or even suffers from energy poverty."

An example of local energy policy that references justice-relevant components can be found in the Seoul Metropolitan Government's 2012 "One Less Nuclear Power Plant" (OLNPP) initiative [77]. Ahn described energy justice as a "pillar" of the initiative, insofar as it was framed around the need for Seoul to become more energy self-sufficient, rather than sourcing power from outside the city via generation and transmission infrastructure that entails "excruciating social conflicts" including "conflict over the construction of high-voltage transmission cable towers in Miryang in southern Korea" [78]. Byrne and Yun described that the policy also sought to "remove unequal burdens among members of a society to enjoy needed energy services," including via the utilization of energy cooperatives and micro-scale solar generation that could be utilized on apartment verandas in Seoul's dense urban setting [79]. They also described that the initiative characterized this commitment using terminology "with the approximate meaning of 'energy fairness,' 'energy equity' and 'energy justice' employed by researchers and some countries in characterizing a social condition or metric for unaffordable energy services for sizable segments of a society." Lastly, the initiative considered citizen participation. In some ways, this appears focused on individual participation in energy efficiency measures. However, the initiative also touted citizen input into policy-making, including the establishment of a Citizens' Commission comprised of "19 reputable figures from civic groups, the business & media arena as well as religious, educational and cultural sectors" [77]. While it is not clear whether this commission advances the voice of marginalized portions of the citizenry, Ahn described this commission as responsible for "leading the policy paradigm shift from an energy saving city to an energy production city, "determining policy directions for the OLNPP initiative, and "reviewing the OLNPP initiative action plans and their revisions and making overall adjustments" [78].

2.4.2. The Potential Role of Microgrids in Operationalizing Energy Justice Principles

These examples illustrate that energy justice can take on a wide variety of contextualized meanings in policy at various scales. None, however, demonstrate that energy policies have yet succeeded in operationalizing the three core energy justice principles identified in Figure 1: procedural justice, distributive justice, and restorative justice [5]. In this framework, energy justice requires that decision-making processes must: (i) fairly and competently incorporate marginalized perspectives and communities (procedural justice); (ii) equitably distribute the benefits and burdens of generation, transmission, distribution, consumption, and other elements of energy systems (distributive justice); and (iii) repair past and ongoing harms caused by energy systems (restorative justice) [5][80][81][82].

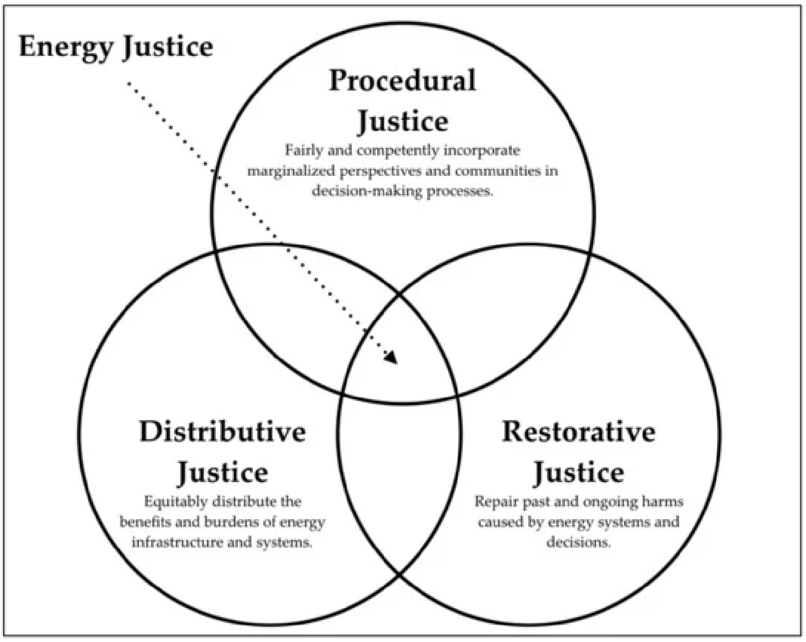

Figure 1. Three core energy justice principles.

Recent literature evidences a proliferation of academic work on energy justice concepts, yet reinforces the conclusion that much work remains in operationalizing these principles. Welton and Eisen, for example, explored various distributive and procedural justice opportunities and challenges in the energy transition, and identified a “paucity” of data on clean energy’s justice implications [83]. They highlighted data gaps on issues such as the definition and distribution of “clean energy jobs,” and they identified a need to pair data on energy poverty and its correlation (or not) with policies related to distributed-scale solar, grid modernization, community solar, and other topics. With respect to the distributive justice implications for siting energy infrastructure, they sensibly noted that “much of the community impact of wind and solar energy turns upon scale—that is, the size of a proposed installation,” and they noted the potential for large-scale renewable energy infrastructure, and its necessary transmission infrastructure, to create a rural/urban energy justice divide. Others, such as Finley-Brook and Holloman, and Zhou and Noonan, have similarly recently identified empirical gaps in understanding the justice implications of energy policy [84][85].

Despite efforts like these to systematically identify energy justice questions, challenges, and opportunities, the potential role of microgrids in operationalizing energy justice principles has received relatively less attention. Wolsink argued that distributed generation microgrids can indeed play such a role, with respect to each of the three energy justice tenets [86]. Identifying microgrids as sociotechnical systems, Wolsink explained that microgrids offer an opportunity to reorganize traditional roles in electricity production and consumption, particularly via the new social relationships within the boundaries of a microgrid (e.g., participation, ownership, management, etc.). Without specific reference to microgrids, Banerjee et al. similarly reviewed ways in which community-scale renewable models can promote justice “by virtue of inclusive participation, collective ownership, and community empowerment” [87]. Welton observed that “the history of electrification counsels that our most successful grid experiments in terms of equity and empowerment may come from focusing on more collective forms of grid participation. Thus, regulators might pay particular attention to programs like community solar and micro-grid formation for the community-scale participation that they embody” [88].

Others have evaluated a substantial potential role for microgrids in promoting energy access via rural electrification [89][90][91]. Venkataramanan and Marnay pointed to micro-utility models pioneered in Bangladesh as “evidence of the relative ease with which grass-roots solar electrification projects can be carried out without heavily subsidized large capital development assistance, when appropriately integrated with community economic development. Similar applications of renewable energy technologies such as micro-hydro, photovoltaic cells, and small-scale wind turbines are well developed and have been deployed widely in the developing world” [92]. This suggests that the microgrid characteristic of flexibility and modularity, discussed above in the context of grid planning and infrastructure, may also be a beneficial characteristic with respect to energy justice, in the form of universal energy access.

The ability of microgrids to account for hyper-localized energy and development needs may render them particularly relevant in the context of island electrification. Veilleux et al., for example, analyzed and cited the potential for microgrids to electrify island communities in places such as Thailand, the Pacific, and Indonesia (where “more than 50% of the unelectrified are believed to live on islands”) [93]. Bertheau, considering the electrification of island communities in the Philippines, concluded that ”100% [renewable energy] systems are a suitable option for electrification and could allow a high energy autonomy and little operational costs” [94]. Moreover, this analysis noted that 100% renewable energy designs often utilize excess generation capacity, creating an opportunity for economic development around non-critical loads, to utilize otherwise curtailed energy that is available at essentially zero marginal cost.

However, even if one assumes or concludes that microgrids foster collective participation, universal access, and a high-penetration of renewables, this does not inherently answer the challenge of energy justice. Questions remain about who can participate in, own, or manage a microgrid; on what terms; and for whose benefit. Here, the flexibility of microgrid architectures presents a challenge as much as it presents an opportunity. Thus, Wolsink and others also identified the need to update other institutional frameworks necessary to organize multiple microgrids—or other renewable energy infrastructure—within a larger energy system (e.g., tariffs, access to capital, etc.) [86][95]. Schnitzer et al., discussing best practices for microgrid development based on seven case studies, identified the following additional “critical factors” for successful microgrid development: “tariff design, tariff collection mechanisms, maintenance and contractor performance, theft management, demand growth, load limits, and local training and institutionalization” [96].

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