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An exploration of how the geographic distribution of power sources impacts power system resilience

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ABSTRACT

The purpose of this paper is to qualitatively explore the question of whether as a power system's sources and energy storage become more distributed, the power system also tends to become more resilient. The paper is divided into two main parts. After presenting introductory material, Part 1 looks at factors that might limit the ability of 'fully-distributed'[1] resources to provide the expected resilience, and Part 2 considers factors that might make a more centralized system more resilient. The key conclusions are:

- The level of distribution of rotating machines that provides the highest resilience may depend on the fuel type.
  - Diesel fuel requires 'fuel maintenance', which may be easier administered at a more central location.
  - Propane does not require the same level of 'fuel maintenance' as diesel, but propane is delivered by truck, and deliveries by truck may be disrupted during severe events. (Diesel is also typically delivered by truck.)
  - Natural gas is typically delivered by pipeline and thus does not have 'fuel maintenance' requirements or the constraints of being delivered by truck, but because it is not typically stored on-site, the resilience of natural gas-powered generators is dependent on the resilience of the natural gas delivery system.
- The key factor limiting the correlation between resilience benefits and level of distribution of photovoltaic and wind generation (with battery storage) is their low energy and power densities, which make it difficult to site sufficient solar and wind near critical loads to keep those loads fully powered during a contingency event. Larger solar and wind fractions can be accommodated if the solar and wind are located where space is available, which may not be near the loads.
- In most cases, battery energy storage systems can be collocated with loads, acting as uninterruptible power supplies at the individual facility level and buffering against faults in the distribution system. Safety considerations are important when batteries are located close to occupied facilities.
- The resilience of the centralized grid is a 'moving target' because of at least two means for improving reliability and resilience that have improving cost effectiveness and that have not yet been fully deployed:
  - Undergrounding of distribution undoubtedly decreases the frequency of outages, and thus increases reliability. There is a tradeoff, though, because undergrounding tends to decrease the outage *frequency* but increase the outage *duration*. Also, in some locations (e.g., those prone to flooding), undergrounding might not always increase reliability.
  - Sectionalizers, normally-open tie lines between distribution circuits, and distribution automation have major potential for increasing distribution system reliability and resilience. These techniques can work with distributed energy resources to create robust resilient microgrids. However, in very rural areas, providing an alternate source via an adjacent circuit is not always feasible (i.e., in rural areas the adjacent circuit is so far away that providing a tie to it is uneconomical or technically unfeasible for voltage drop reasons).
- Because of load diversity, the total amount of generation required to meet the load demand is *much* less when resources are shared than is the case if each facility has its own generation.

[1] In this document, "fully distributed" resources are ones collocated with the loads they serve.

Thus, generation costs can be reduced if generation sources serve multiple loads, and if generation sources can share loads. Ensuring that the ability to share loads still exists during an emergency will typically require some distribution system hardening means to be employed.

ACKNOWLEDGEMENTS

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ACRONYMS AND TERMS

Acronym/Term	Definition
BESS	Battery Energy Storage System
DER	Distributed Energy Resource
DF	Diversity Factor
FLISR	Fault Location, Isolation, and Service Restoration
GFL	Grid Following
GFM	Grid Forming
MTTF	Mean Time To Failure
PV	PhotoVoltaic

INTRODUCTION

This report documents the results of a project that explored the optimum level of distribution of power system assets. The question that was presented was, "Is a more distributed power system *always* more resilient?". This paper explores answers to this question. The focus will be on resilience that mitigates the effects of high-impact, low-probability events including long-duration outages (lasting 6 to 24 hours), and extended-duration hours lasting longer than 24 hours [97], although many of the topics discussed here are also applicable to shorter-duration interruptions.

Throughout most of the 20th century, the North American power grid evolved into and remained in a highly centralized architecture, like that shown in Figure 1. In this architecture, power is generated at large, centralized power plants, dispersed over a large area using a high-voltage transmission system, and then delivered from that high-voltage transmission system to end customers (loads) using a medium-voltage distribution system that connects to the high-voltage transmission at distribution substations through substation transformers. The high-voltage transmission system is typically networked, as shown in Figure 1, which provides more than one path from the generation sources to the distribution substations. Distribution, on the other hand, is typically radial, meaning that there is only one path from the distribution substations out to their end loads.

It is often accepted as axiomatic that a more distributed power system is a more reliable or resilient one because as power sources are moved electrically closer to the loads they serve, there are fewer miles of transmission and distribution lines that can be interrupted by weather or other events, and fewer transformers, fuses and other components to fail. If one takes this reasoning to the extreme, the maximum levels of resilience and reliability are achieved if every load has its own power source, a "source-per-load" or "fully distributed" scenario, as shown in Figure 2 which shows the same power system as in Figure 1 but with grid forming (GFM) assets collocated with most loads (larger grid-forming assets are labeled "GFM" and smaller grid-forming assets are labeled "M" in Figure 2). Under non-contingency conditions, these sources could be shared with the larger grid according to an optimal economic dispatch scheme. Under contingency conditions which could include anything from local feeder outages to systemwide catastrophic events, the distributed energy resources (DERs) could be shared between loads using whatever portions of the system are still intact. In the absolute worst case, every load stands alone using its own local resources. At least in theory, this source-per-load situation seems to be one that would provide the highest level of resilience and reliability. However, practical considerations may impose limits on the real-world performance of highly distributed systems under contingency conditions. For example, all sources of power require maintenance, and poor maintenance will lead to poor reliability and readiness. Maintaining large numbers of geographically-dispersed and diverse small units may be more difficult than maintaining a smaller number of less-diverse centralized larger units to which maintenance crews can be dedicated and for which parts can be stockpiled. As another example, for most facilities, the physical footprint of a PV or wind power system that meets a significant fraction of the facility's needs off-grid would be larger than the available physical space. Facility-level backup power for these facilities would entail combustion-based rotating machines, and the ability to meet resilience goals might be constrained by decarbonization or emissions goals and the need to store and maintain significant amounts fuel on-site.

Also, it should be borne in mind that a generator used strictly for backup purposes is sitting idle for most of its lifetime; because it runs only during emergencies and emergencies are infrequent, the backup generator actually provides very little energy. Because the cost of a backup unit is spread over so little energy, its cost per unit energy is quite high. Granted, the *value* of that energy can be quite high because of when it is supplied (during emergencies when the alternative is a blackout), but still, this cost could potentially be reduced if the generation resource could be better utilized.

It might be the case that a hybrid approach, such as shown in Figure 3, might lead to better resilience outcomes. The hybrid approach would involve pushing some assets such as energy storage far out to the grid edge, as close to the loads as possible, but would locate other assets including PV, wind and combustion-based units at intermediate buses—perhaps at distribution substations or even on their subtransmission circuits. The generating units on intermediate buses could be maintained more professionally and regularly, and would be freer of space constraints that frequently occur closer to load endpoints.

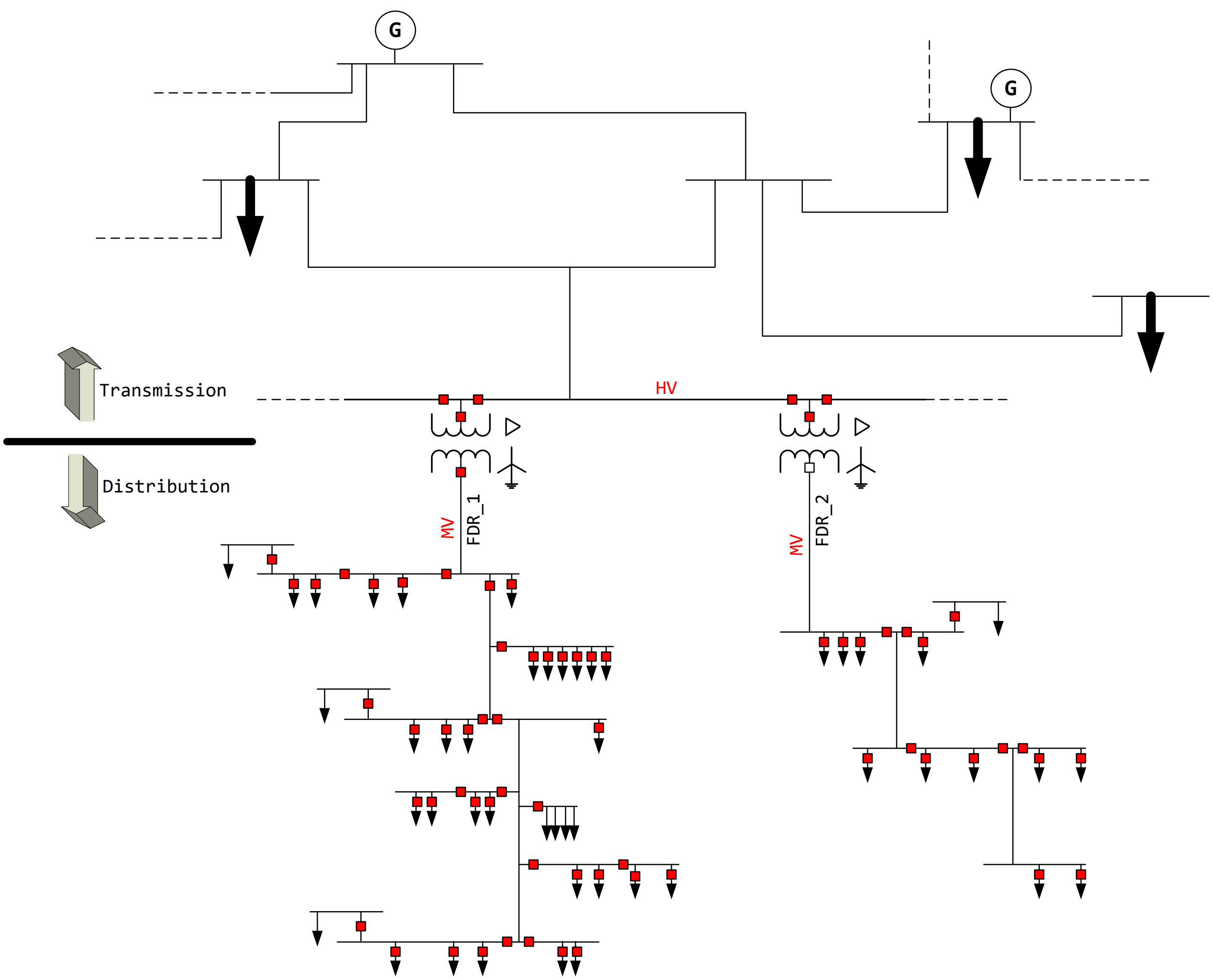

Figure 1. Centralized power system architecture, representing the historical configuration of the North American grid.

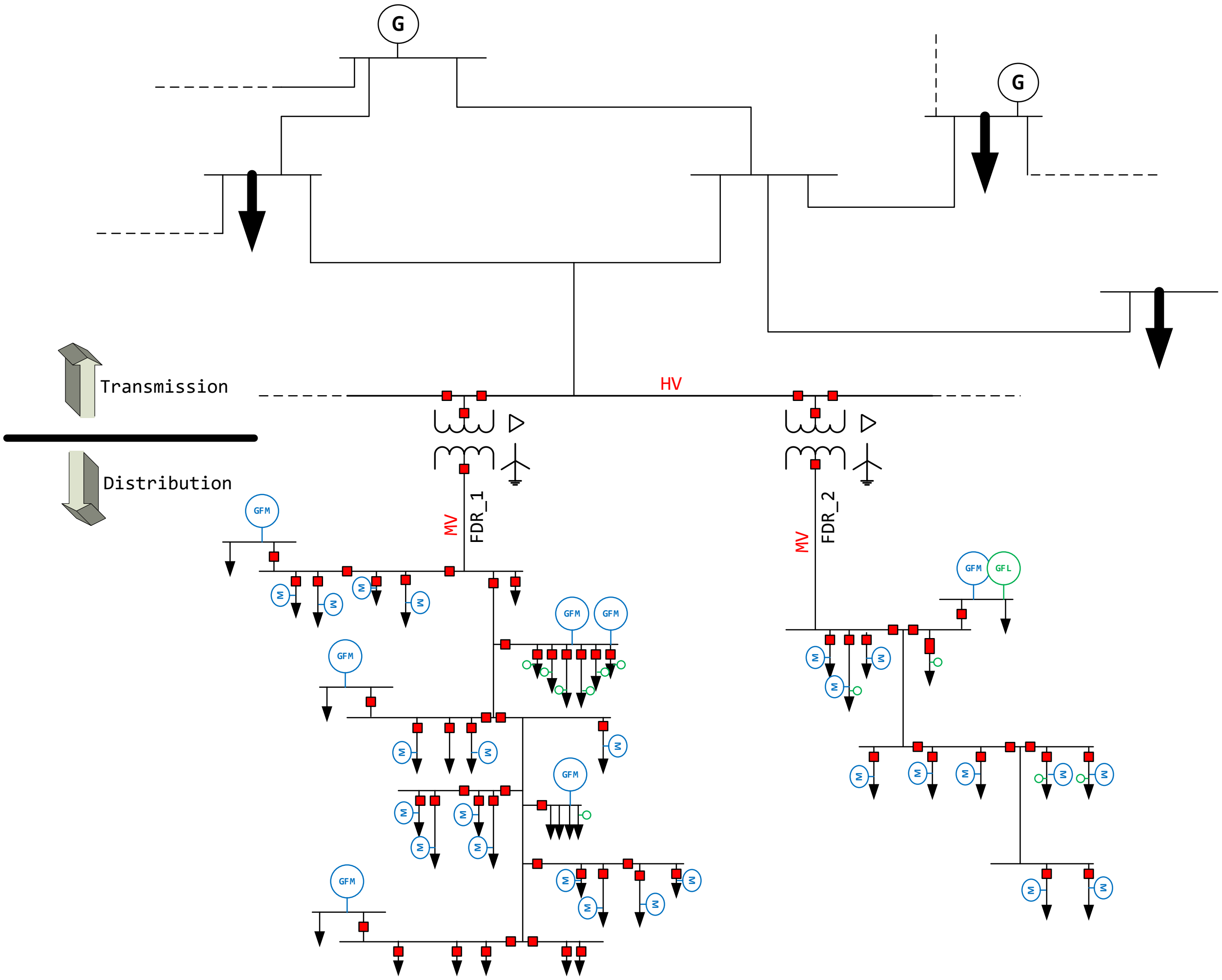

Figure 2. Decentralized architecture in which distributed generation is located at individual load endpoints. This might be called a "fully distributed" architecture. GFM = grid forming; GFL = grid following. The small circles labeled "M" are all grid-forming assets. The small green circles are facility-located grid-following assets.

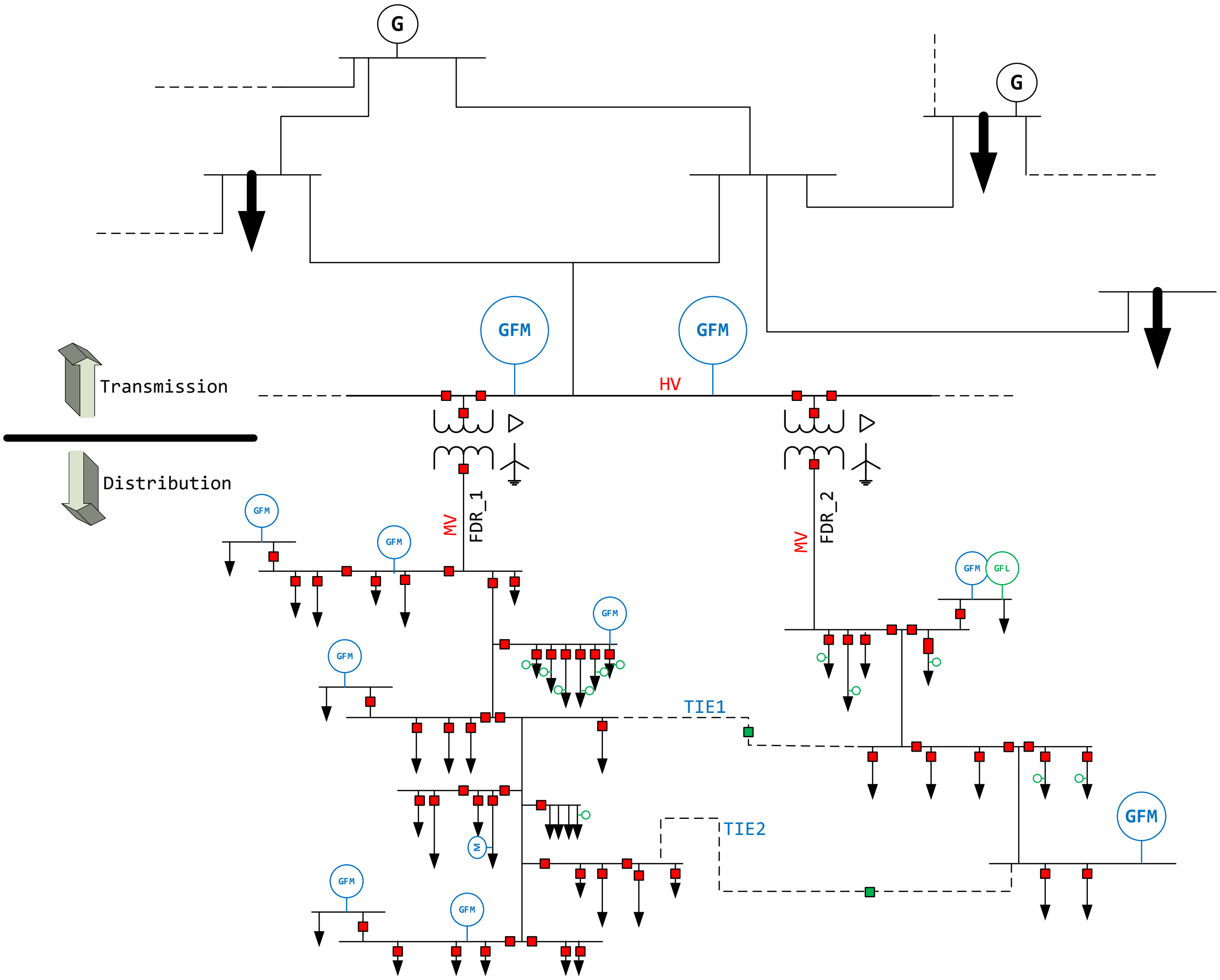

Figure 3. Hybrid architecture in which grid-forming assets are located at the feeder or community level. GFM = Grid Forming, GFL = Grid Following. The small green circles near some loads are facility-located grid-following assets. Tie lines have been added in this architecture.

Note also that Figure 3 also contains tie lines with normally-open breakers. Tie lines and distribution system automation provide redundancy in the path between centralized sources and distributed loads. These techniques and their use will be discussed more fully in Part 2 of this paper.

1. FACTORS THAT LIMIT THE RESILIENCE BENEFITS OF DISTRIBUTED ENERGY RESOURCES

1.1. Maintenance

A key factor that might drive toward a compromise between distributed and centralized architectures is in the ability to keep DER equipment and DER fuel maintained and mission-ready. DER technologies have differing maintenance needs, and thus whether maintenance favors centralization depends somewhat on the DER technology.

1.1.1. Generator maintenance

When high continuity of power service to a specific facility is desired, a backup generator is a very common solution. Backup generators are inexpensive relative to other forms of on-site power backup [52,53], they are fully dispatchable, the technology is highly mature, and generators are available for a wide range of applications. Backup generators that run in parallel with the grid *only* for periodic testing and maintenance purposes are exempted from the requirements of IEEE Std 1547-2018 [12]. Generators take advantage of the fact that their energy storage medium, chemical fuel, has a very high volumetric and mass energy density, which makes storing relatively large quantities of energy on-site more economical.

Backup generators are typically collocated with the loads they serve, behind a transfer switch that disconnects the loads and generator from the grid in the event of a grid outage. Because most outages originate with problems in the distribution system [38,48], one might intuitively expect that maximum reliability and resilience would be obtained if every facility had this kind of backup generator, with each generator having sufficient local fuel storage to enable it to serve the load for the desired period of off-grid operation. In that sense, one might think of a one-generator-per-facility case being a "base case" of sorts.

The reliability of backup generators is discussed in IEEE Std 3005.4-2020 [101]. It is both intuitive and well-documented that the resilience and reliability benefits provided by engine-driven generator sets can be seriously eroded if the generators are not properly maintained [1-3, 8]. References [1] and [8], which describe the same body of work, looked at three datasets containing information on the reliability of three sets of diesel generators with different maintenance regimes. This work indicated that well-maintained diesel generators had a low-end mean time to failure (MTTF) of 1180 hours, more than 22 times higher than poorly-maintained units which showed a low-end MTTF of 53 hours. Put into terms that are important for resilience, a well-maintained generator might be reasonably expected to provide 49 days of off-grid operation, but this can drop to just over 2 days for a poorly-maintained generator [1]. Furthermore, poorly-maintained generators were found in this work to have a probability of failing to start of as high as 1.88%, whereas for a well-maintained generator that probability is an order of magnitude less, at about 0.17%.

The off-grid generator running time will also be limited by the amount of fuel that can be stored on-site. For emergency backup generators, NFPA 110[2] requires that the fuel tank be sized to hold 133% of what is required to meet the minimum off-grid run time for that generator [58]. Storing tens of thousands of gallons of diesel on-site (not to mention maintaining that quantity of fuel, which is

[2] NFPA 110 was written for emergency generators and thus it may or may not apply to diesel generators used in a grid resilience scheme such as is contemplated here. Still, NFPA 110's requirements provide an instructive starting place.

covered in the next section) may be undesirable or impossible for some users. Thus, considering the MTTFs of well-maintained generators as just described, it seems likely that in many cases the amount of on-site fuel storage, not MTTF, will be the limiting factor in how long a diesel generator can run off-grid.

On the question of whether greater distribution leads to greater resilience, then, the question one must ask is whether reliability and resilience are better if generators are more centralized because maintenance is easier, less expensive, or more likely to be performed. It seems intuitively obvious that centralizing generators would make service and maintenance easier, but most generator manufacturers and vendors offer maintenance and service contracts to generator owners, under which qualified personnel come to the generator site periodically (typically once/year) and perform routine maintenance and functional checks on the generator. Furthermore, most modern generators have digital controllers that "self-exercise" the generator periodically (e.g., start and run the generator for a short time once a week), thereby automatically performing part of the routine maintenance. Most of these controllers can automatically communicate to the generator owner if an issue is discovered during this periodic exercise, which increases the likelihood that a problem can be corrected before the generator is needed in emergency or resilience service.

It should also be mentioned here that engine-generator set maintenance requirements are a function of how highly loaded the generator is. Operating generators for extended periods of time at the bottom end of their power range can significantly increase the need for periodic maintenance [95]. It is thus desirable to keep the generator more highly loaded while it is in operation. Potential means for doing this include the following:

- Share a generator among many loads. Load diversity can be used to keep a genset operating at a more optimal power level. This is discussed further below, but the issue is mentioned here because sharing a generator among loads would be a strong driver toward a higher degree of centralization.
- Utilize energy storage [96]. If battery energy storage is used with a generator, the generator can be used to charge the batteries, operating the generator at a near-optimal loading during most of the charging cycle. The batteries then provide the instantaneous power demand of the load. This is only a partial solution because for most batteries, optimal charging includes a period of low-current charging near their full state of charge, which may require low-load operation of the generator.
- Use several smaller generators, instead of a single large one. During lower-load periods, some of the units can be turned off, leaving others to carry the load at a more optimal loading level.
- Manage the load. The generator can be turned off for part of the time and then on for part of the time, shifting the electrical load to the generator-on periods and leading to higher generator loading during those periods.

On balance: maintenance is critically important, but industry provides manual and automated maintenance services that likely will make the MTTF longer than the longest off-grid operating periods typically required. The most important factor here is that maintenance requirements are minimized if it is possible to avoid operating the generator for extended periods of time at low load, and this is much easier to do with a more-centralized generator due to load diversity (see section 3 of this paper, page 21).

1.1.2. *Fuel maintenance*

Diesel generators have many attractive properties. They are available over a wide size range, from 20 kW up to nearly 6 MW. Diesel engines are highly robust with long service lifetimes, and their torque and transient-response characteristics match up well with the needs of the electricity generation application. Also, diesel fuel is readily available worldwide. Diesel generators can use so-called 'red diesel', which is dyed red to distinguish it from diesel for use in on-road vehicles. Red diesel is typically less expensive than highway diesel because it is subjected to lower taxes [55]. Given these considerations, it is not surprising that the majority of on-site engine-generator sets are diesel-powered.

One key disadvantage of diesel-fired generation from a resilience perspective is that diesel fuel has a shelf life that is short relative to the time periods for which fuel must be stored. Diesel storage containers must be vented to the air, which provides a path for moisture to enter the tank [56]. This moisture settles to the bottom of the tank, where it can provide a breeding ground for microbes that feed on the fuel. When these microbes die, they settle to the bottom of the tank and eventually create a biomass sludge that produces harmful acids. It is generally accepted [4] that diesel should be used within six to twelve months, and NFPA 110 requires that fuel quality be tested annually [5], but diesel fuel used in standby applications is often stored for considerably longer than that [6].

Running a diesel generator on degraded fuel can lead to a failure to start, a failure to carry load, or physical damage to the engine. Thus, for diesels and gasoline-powered generators, degraded fuel is a key risk to achieving high resilience in the field.

Also, delivering diesel fuel to widely-dispersed generators is typically done by truck. This is more costly than delivery to a central location, which can be done by truck, rail, or pipeline, and during severe contingencies it is more likely that fuel deliveries by truck to widely dispersed generators will be disrupted than deliveries to a more centralized location [57].

Some small backup generators, usually in the 5 kW to 10 kW range, are gasoline-powered[3]. Gasoline has a shorter shelf life than diesel [14], although some sources claim that gasoline in a generator's tank can have a shelf life of up to a year with proper additives [7]. Because gasoline is only used in very small generators, gasoline-powered generators are always deployed in a highly distributed mode and are thus not considered further here.

Propane is another popular fuel for smaller backup generators, with units commercially available up to 140 kW. Propane is unique in that it does not have many of the degradation mechanisms associated with other fuels, and thus it has an extremely long shelf life. This may mean that the optimal level of distribution of propane generators is different than for generators running on diesel or gasoline, although propane is also delivered to most sites by truck, so the issue of disruption of delivery by truck during severe events is the same for propane as for gasoline or diesel[4].

Natural gas is another commonly-used fuel for backup generators, in applications where delivery of natural gas by pipeline is available. Many smaller backup generators, particularly residential-scale units

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[3] Gasoline-powered generators are available in larger sizes, up to ~400 kW, but it appears that these are used only in specific applications where diesel is not an option, and are thus rare.

[4] Propane truck delivery disruptions caused by severe weather during the winter of 2022-2023 caused major challenges for remote mountain residents of California and on Native American reservations in South Dakota.

less than 20 kW[5], are fueled by natural gas. Receiving their fuel from natural gas pipelines avoids both the "old fuel" problem[6] and the issues of delivery by truck. Delivery by pipeline does create a "dependent infrastructure" issue: because most natural gas-fired backup generator installations do not include on-site gas storage, if electricity is out for an extended period of time over a wide area then natural gas supplies could be disrupted and resilience could be adversely impacted. Such dependent-infrastructure issues contributed to the ERCOT blackout in February of 2020 [15], and the electricity-gas interdependence becomes more of an issue as one moves farther from the source in the gas-supply network [16]. Data available to date suggest that in general the gas-supply infrastructure is more resilient than electricity-supply infrastructure, and gas outages to backup generators caused by a loss of electrical power remains relatively rare[7] [16].

There are also generators that are able to run on more than one fuel, thus mitigating the risk of being dependent on a single fuel source. For example, there exist generators that are designed to run primarily on natural gas, but in the event of a widespread event that disrupts gas supplies, the generator can be run on diesel fuel [66].

This list of fuels is non-exhaustive, and alternative fuels are actively being developed. Although emissions limits on stationary emergency generators do not apply during emergencies [86], alternative fuels may eventually provide a path to provision of resilient electrical service with a higher degree of environmental sustainability. The "brass ring" in this respect is hydrogen produced by solar-driven electrolysis of water, a process that is well-known but which today produces hydrogen at costs that are far too high to make it a viable contender in the energy marketplace [98], and there is as yet no clear pathway to reducing these costs[8]. It has been demonstrated that it is possible to produce ammonia using solar power, water, and nitrogen from the ambient air [67]. Ammonia is a promising low-carbon energy storage medium that can be efficiently converted to electricity using a fuel cell [68], although its promise is moderated by the fact that ammonia itself has several highly undesirable properties. Another potentially promising alternative fuel is dimethyl ether (DME) [69]. DME appears highly promising in many respects. It is relatively nontoxic and is not a greenhouse gas, it can be handled similarly to liquified propane gas and does not require cryogenic temperatures like liquid natural gas does, and it burns in compression-ignition engines (like diesel) but produces far less soot than diesel does [70]. DME is largely chemically inert and has a very long storage life, similar to propane, and thus like propane it should have a minimum fuel-maintenance burden when used for power system resilience purposes. It has also been demonstrated that DME can be made from a wide variety of feedstocks [69], potentially providing pathways to using DME as a low-carbon energy carrier. The key drawbacks to DME are that: a) its volumetric and mass energy densities are significantly lower than those of either diesel or propane, requiring storage of more fuel to obtain the same off-grid automonous operation period; and b) there is almost no infrastructure for making, shipping, and consuming DME, whereas there exists considerable infrastructure for handling ammonia because of its widespread use in agriculture. In general, alternative fuels can enable generators to provide resilient electric power service with a much smaller environmental footprint, but the costs of the alternative fuels tend to be far higher than those of fossil fuels, and thus the markets for these alternative fuels have been slow to develop.

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[5] Gas-fired backup generators are available in sizes up to at least 60 kW.
[6] Natural gas also has a very high shelf life.
[7] Interestingly, part of the reason for the higher resilience of the gas infrastructure is that its sources are more distributed.
[8] There is also some question as to what to do with the large amount of oxygen that would be produced if hydrogen were generated via electrolysis on a scale sufficient to meet a large fraction of today's energy demand.

The take-away from this section is that whether fuel maintenance is a driver toward higher degrees of centralization is dependent on the fuel. There might be a weak driver toward centralization for diesel-based generators on the basis of fuel maintenance, but for propane and natural gas there is no such driver. Furthermore, industry does offer diesel fuel maintenance service which, if used, greatly reduces the risk of loss of generation function due to old diesel fuel. Dual-fuel generators can further reduce risks posed by fuel supplies, and future advancements into alternative fuels may shift the conversation.

1.1.3. Maintenance of PV

Photovoltaics (PV) have several major advantages over engine-gensets. Apart from the obvious reductions in on-site emissions during generation, PV also requires zero fuel maintenance and relies on no external fuel delivery infrastructure. In theory, a PV + storage system could sustain itself off-grid indefinitely, if the loads on the system are managed to remain within the energy provided by the sun. In this section, we consider whether some level of centralization, such as community solar plants or subtransmission-connected PV serving multiple substations, might provide benefits in making PV more resilience-ready due to maintenance considerations.

PV modules themselves tend to be low-maintenance, but PV plants do require some maintenance, including repair, adjustment or replacement of inverters and meters, replacement of blown fuses, tightening of loose connections, repair of damage due to electrical stresses, and other items [72], [76]. PV plants tend to have modular designs, especially if module- or string-level inverters are used. Thus, failures of some of the aforementioned items tend to lead not to a complete loss of output from the PV plant, but instead to a degradation of performance (effectively a lowering of the plant's conversion efficiency). This is good in one sense, but this reduction in output is only detected if the plant is being closely monitored, *and* the party performing the monitoring has the ability to generate reasonable values for the predicted or expected PV plant output. Without these two items, issues within PV plants may go undetected for significant periods of time. Field data on large numbers of PV plants suggests that larger "utility scale" PV plants tend to exhibit much lower values of lost energy due to these intra-plant issues than smaller plants, and that this difference can largely be attributed to better monitoring of the larger plants [72]. It was mentioned above that generator vendors tend to provide post-installation maintenance services under contract, but it appears that this type of service contract may be less common for distributed PV plants. Thus, on balance, the readiness of a PV plant to contribute to resilient electric power service during severe events might be better for more centralized plants than for fully distributed ones.

It should also be borne in mind that PV plants by nature are more exposed to the elements than, say, an engine-genset. Severe storms that produce damaging winds leading to a need for power system resilience may also produce large hail or other events that could damage a PV array [77], [78]. It is not yet clear whether this factor is a driver toward greater centralization because of things like ease of access by maintenance crews both before [78] and after the event and higher likelihood that stocks of spare parts have been locally maintained, or a driver toward greater decentralization because events like large hail tend to be localized and spreading the PV around an area might lead to some of it not being exposed to the event.

For completeness, it should also be mentioned here that PV, unlike backup generators, is commonly operated grid-parallel. Thus, in addition to the "black-sky" resilience benefits discussed in this paper, PV can also provide economic benefits to its owner on "blue-sky" days via reduced power consumption and/or power sales to the local system operator. As noted above, backup generators typically provide only the "black-sky" resilience benefits. A detailed discussion of these economic benefits is beyond the scope of this paper, except to consider whether these "blue-sky" benefits would tend to favor more centralized or more distributed plants. Fully-distributed plants would provide economic benefits to the owners of the facilities with which the PV plants are collocated, but there are well-known business models for distributing the benefits of a more centralized PV plant to multiple stakeholders [85]. Thus, while the "blue-sky" economic benefits of a PV plant do reduce the energy costs from PV, they probably do not provide a strong driver toward either centralization or decentralization.

1.1.4. Maintenance of wind turbines

Wind turbines experience high stresses in operation, which causes relatively high failure rates of a number of key components [73]. For large turbines (> 1 MW [75]) in large wind-power plants (so-called "utility scale" land-based wind power plants), real-time monitoring to detect and predict failures is an essential element in maintaining plant readiness and maximum energy production. Large wind-power plants are equipped with anemometry for wind-resource measurement, and the turbines in such plants are typically fitted with an array of sensors that help to monitor each wind turbine's condition [73]. These plants also have ready access to maintenance staff who have the skills and equipment required to service turbines *in situ*. These factors can significantly reduce the time to repair and the lost energy production in these plants.

However, smaller, community-scale wind plants (so-called "distributed wind") often do not have such monitoring or dedicated monitoring and maintenance staff. In particular, installations using small (< 100 kW) or medium (0.1-1 MW) wind turbines rarely have the benefit of such monitoring; many lack even basic anemometry, and are monitored only via their energy production measured at the meter [74]. Thus, in plants of this type, issues often go undetected until a failure occurs that reduces a turbine's output to zero. Also, if a small wind turbine fails atop a tower that cannot be tilted down to enable ground-level repairs, the cost of repairing the small turbine can exceed the value of the turbine, which has led to a number of small wind turbine installations being abandoned in-place.

It should also be noted that wind capacity factors tend to rise as the size of the wind turbine increases. This trend is due to a complex combination of factors, including where small turbines tend to be installed (not necessarily on sites with the best wind resources), the hub height (smaller turbines tend to be on shorter towers where the wind resource is not as good), and the aforementioned differences in the ability to monitor and maintain large versus small wind turbines.

Finally, it should be noted that wind turbines must be exposed to the elements to function. They are thus susceptible to damage from severe weather, in particular high winds [79],[80] and lightning [81],[82]. It is unclear whether this factor is a driver toward or away from greater centralization, but it should be considered when determining whether wind can be an effective resilience-enhancement technology in specific locations.

All of these factors taken together suggest that there is likely some resilience benefit from wind turbines being more centralized, in the form of increased readiness to provide power under emergency conditions, although for this work there was insufficient information to quantify this benefit.

1.1.5. Maintenance of batteries

PV and wind power systems used for off-grid operation generally have to be coupled with energy storage that enables energy to be collected when available and then used whenever needed. This storage is usually in the form of batteries. Batteries have their own maintenance requirements that vary from one battery chemistry to another.

Lead-acid batteries have been used for many years in stationary backup power applications, and their maintenance requirements in standby [83], [84] and PV [88] applications are well-known. The users of these batteries typically have maintenance staff who apply the relevant maintenance, testing, and replacement procedures.

Most residential and commercial applications today use lithium-ion batteries. The maintenance requirements for these are less mature and are still being standardized [89], but they are typically less than those for lead-acid batteries—in fact, some manfacturers state that their small lithium-ion battery systems for residential use require no pre-scheduled or preventative maintenance, other than ensuring that air intakes and exhausts are not blocked [90]. For these battery systems, maintenance-related factors are not an obstacle to collocating the energy storage right next to the loads served.

1.2. Space constraints

A key factor that might drive toward a compromise between distributed and centralized architectures is the low energy and power density of PV and wind resources. Both require large land areas to produce significant power, and in many resilience applications there may not be enough available land collocated with the loads to fully distribute PV and wind.

PV (with energy storage) can be very attractive as a means for increasing the time period over which a power system could operate off-grid, primarily because PV+storage requires no external fuel input other than sunlight, eliminating issues associated with old fuel or disruption of fuel delivery during events[9]. However, PV has a low area energy density, meaning that the land area per unit energy provided is high relative to other types of generation. This low energy density can limit the ability to collocate PV with loads in sufficient amounts to provide high resilience benefits.

To better understand this constraint, consider an example of a small community hospital that is in an area with limited power reliability. Hospitals are often considered critical infrastructure and thus have high power resilience needs. For this example hospital, consider the possibility of using a PV + storage plant to provide power when the connection to the main grid becomes unavailable. The focus here is on the land area required for the PV array. The calculations will be done on an energy basis, so there is a built-in assumption that energy storage would be used to make the PV-generated energy available whenever it is needed.

A typical hospital uses on the order of 75 Wh of electricity per day per square foot [19]. A typical hospital needs on the order of 2500 ft^2/bed [20], so a 50-bed hospital, which is a common size for a small community hospital, would be a roughly 125,000 ft^2 facility (about 11613 m^2), which would translate to an approximate average daily electricity usage of 9.4 MWh/day. If we assume Albuquerque's solar resource levels and utilize typical irradiance data, the PVWatts online calculator

[9] PV can also provide economic value while on-grid under normal operating conditions. However, the focus of this paper is on resilience attributes, and thus these on-grid, "blue-sky" benefits, while real, are beyond the present scope.

indicates that a PV array that can be expected to produce about 9.4 MWh/day in all months would be a 2.25 MW plant with a tilt angle of 40^o and a due-South azimuth. A PV plant of this size typically requires a minimum of 5 acres/MW (20234 m^2/MW) [21], so the PV plant that would supply this hospital when off-grid would require just over 11 acres (44515 m^2).

For a lower-irradiance small community, such as Ivanhoe, MN, again using PVWatts, this same hospital would need a 4.25 MW PV plant tilted at 50^o, requiring just over 21 acres (84984 m^2).

It is not difficult to imagine that most hospitals would not have this land area immediately available for development into a PV plant. One space-saving option that might be considered would be to cover the parking lot of the hospital with a PV shade structure. A reasonable estimate of the number of parking spaces per 1000 ft^2 of building footprint for a medical office building is 5 spaces/1 kft [22], and a rule of thumb for the minimum parking lot size is 300 ft^2 per parking space [23]. Thus, the example hospital would require 675 parking spaces, and the minimum parking lot size would then be on the order of 202,500 ft^2 (18813 m^2). These values are collected in Table 1. For the case of Albuquerque sunlight, the ratio of the parking lot size to the required PV array size is 0.42, and for the case of Ivanhoe sunlight that ratio drops to 0.22. Based on these rough estimates, it appears unlikely that covering the parking lot with PV would be sufficient to meet the off-grid needs of the hospital.

Table 1. Numerical values used in the hospital example.

Parameter	Value (m^2)
Hospital size	11613
Parking lot size	18813
PV array size (Albuquerque)	44515
PV array size (Ivanhoe)	84984

In fairness, nobody would ever try to design a purely PV + battery off-grid system for a load this large. The cost per unit energy of a stand-alone photovoltaic system rises quickly as the system is designed for increasing availability, becoming almost exponential as the designed-for availability exceeds 95% [24-26]. For this reason, large loads are almost never powered off-grid exclusively by a PV + battery system. Instead, a load as large as the hospital considered here would be powered off-grid by a hybrid system including PV, energy storage, and a generator. The central point of this discussion is that because of PV's low energy density, it is probably not possible to collocate with the hospital a PV array that is large enough to power a significant portion of the hospital's power needs when operating off-grid. Thus, a larger, centralized PV array coupled with energy storage likely makes more sense. (Note that it is not necessarily the case that the PV's energy storage needs to be centralized; this is discussed more fully below.)

Wind turbines with storage might be another option that could be considered, and again, it is assumed that the wind turbines would be used in conjunction with energy storage. According to the U.S. Geological Survey [61], the average size of a wind turbine put into commercial operation in the US in 2020 was 2.75 MW. In New Mexico, wind plant capacity factors are at their minimum in October, at which time the capacity factor is about 17.5% [62]. A 2.75 MW wind turbine operating at a capacity factor of 17.5% would produce about 11.5 MWh/day, so this single turbine with energy storage could be sufficient to meet the energy needs of our hypothetical example hospital. However, there are restrictions regarding where a wind turbine can be built. In most jurisdictions, there is a minimum distance called a "setback" that must be maintained between wind turbines and buildings, roads, airports, parks, wetlands, and other structures and areas [59,60]. Some setback requirements are expressed as a multiple of the maximum height of the wind turbine, which is the hub height plus half the rotor diameter. The average hub height for wind turbines in the US is 90 meters [63], and a 2.75 MW wind turbine can be expected to have a rotor diameter on the order of 120 meters [64], so the 'height of the wind turbine' for this example 2.75 MW machine would be 90 m + 60 m = 150 m ≅ 500 ft. Using one specific example [65], a non-exhaustive list of requirements includes that a 2.75 MW wind turbine must be:

- At least twice the height of the wind turbine away from any on-site occupied building (1000 feet for our example).
- At least five times the height of the wind turbine away from any occupied building on any adjacent property (2500 feet for our example, or just under half a mile).
- At least twice the turbine height away from any public right-of-way (for our example turbine, 1000 feet).

Consider the 1000-foot setback. This setback requires that our example 2.75 MW wind turbine be at the center of a circle of radius 1000 feet in which there are no occupied structures or public rights-of-way. That circle has an area of $\pi \times (1000)^2 = 3{,}141{,}593\ ft^2 = 72.1$ acres. It is highly unlikely that such a circle exists near our example hospital.

The conclusion that can be drawn from the foregoing is that because of space constraints, it is likely that PV or wind plants sufficient to provide significant extension of off-grid operating time for a microgrid serving energy-intensive critical facilities like hospitals will need to be located some distance from the critical load, and centralizing these plants probably makes sense in most cases. Techniques for improving the reliability of the connection between the remote PV and the critical load and/or energy storage (undergrounding, provision of redundant source-load paths, and so forth) will need to be considered in this case.

1.3. Safety

A key factor that might drive toward a compromise between distributed and centralized architectures is the safety of energy storage technologies, and in particular lithium ion batteries. Battery fires are rare, but they do occur, and when they do the results can be catastrophic if the energy storage is collocated with a human habitation or workplace.

1.3.1. Battery safety

It is well-known that if energy storage were available at every facility, the power system could be fundamentally transformed from a *power* delivery system into an *energy* delivery system, with instantaneous power demand decoupled from the instantaneous output of energy storage. This could improve the efficiency of generating sources, facilitate the increased utilization of intermittent sources, and improve the capacity utilization of grid assets. It is not an overstatement to say that the availability of low-cost, reliable, safe, sustainably-made, electricity-to-electricity energy storage systems would revolutionize the way electric power is provided.

Historically, off-grid stationary electric power storage has been provided by lead-acid batteries [25]. This technology is highly mature, well-understood, field-proven, and well-supported by a worldwide network of manufacturers, distributors, and service organizations [71]. Lead-acid batteries are largely recyclable, and are recycled at high rates worldwide [71]. There are certain safety risks with lead-acid batteries, but these are well-known and have highly mature mitigation strategies. However, lead-acid technology suffers from very low volumetric and mass energy densities and relatively short cycle lifetimes.

Lithium-ion batteries have quickly become a leading technology for providing this service because they have higher energy and power densities and longer cycle lives than lead-acid and other competing alternatives. There exist today high-resilience grid solutions that utilize lithium-ion batteries located at individual facilities [28], so distribution of battery-based energy storage all the way to the grid edge for resilience purposes is already being demonstrated in the field.

However, if a high-energy-density lithium-ion battery is damaged, contains certain manufacturing defects, or is exposed to extreme temperatures, then there exists a mechanism that can lead to thermal runaway, which can cause these batteries to catch fire or explode [91-94]. Although lithium battery fires are rare, there have been a number of fires in lithium-ion battery facilities for grid storage that have generated a significant amount of publicity [29-31]. There are significant challenges involved in extinguishing lithium-ion battery fires [54]. They burn very aggressively, the fire generates toxic and explosive gases, and lithium battery fires have been known to re-ignite days or even weeks later.

Codes and standards have been and are being developed to minimize the risks associated with systems of this type [54]. A key example is NFPA 855, which states that its purpose is to provide "… the minimum requirements for mitigating the hazards associated with ESS and the storage of lithium metal or lithium-ion batteries" [32]. NFPA 855 applies to lithium-ion battery systems with more than 20 kWh of aggregate capacity, which may exclude a number of residential-scale energy storage units (a Tesla PowerWall 2, for example, has a nameplate capacity of 13.5 kWh [33]). Certification standards for energy storage systems also exist and are being continuously updated and improved based on new industrial learning. These include UL 991, "UL Standard for Safety Tests for Safety-Related Controls Employing Solid-State Devices"; UL 1973, "ANSI/CAN/UL Batteries for Use in Stationary and Motive Auxiliary Power Applications"; UL 1998, "UL Standard for Safety Software in Programmable Components"; UL 9540, "UL Standard for Safety of Energy Storage Systems and Equipment"; and UL 9540a, which is a test-method companion to UL 9540 [54].

It might be the case that end users might not be comfortable with having significant energy storage collocated with human habitations and workspaces, due to safety considerations. One recent example of a proposed battery energy storage system (BESS) for resilience in rural New York is instructive. The utility serving that area proposed a 20 MW, 40 MWh BESS plant for reliability and resilience improvement. Local residents, including the local fire chief, expressed significant concerns about this battery plant, many of them focused around the possibility and management of battery fires in a sensitive and potentially wildfire-prone environment [34]. Some of the local residents were sufficiently concerned about battery fires and other issues that they started a petition to block the BESS project, an effort that was ultimately successful.

1.3.2. Fuel safety

All of the fuel types discussed above carry their own safety risks [35-37]. All fuels are flammable, of course, so there are always explosion and fire risks associated with any stored fuel, and appropriate precautions need to be taken to ensure that stored fuel is not exposed to any ignition sources. The vapors from liquid fuels, and gas-state fuels themselves, tend to have serious adverse health effects if inhaled, so there are usually ventilation requirements for stored fuel. Liquid fuels can create a number of health and environmental problems when spills occur, so for diesel and gasoline there are requirements for prevention and cleanup of spills.

These hazards may favor applications in which the fuel can be stored away from occupied spaces or areas of high human activity, so this would seem to favor more centralized generation. However, people today live with significant amounts of stored fuel in gasoline cans and gas tanks, propane tanks, and pressurized natural gas lines near human-occupied spaces, suggesting that a comfort level has been reached around living near such fuel storage. It may also be a factor that battery fires tend to generate a lot of press exposure, whereas fuel explosions or accidents seem not to generate such coverage.

2. FACTORS THAT WOULD IMPROVE THE RESILIENCE OF A MORE CENTRALIZED SYSTEM

As was noted above, the focus of this paper is to explore the question, "Is a more distributed power system *always* more resilient?". Embedded in that question is a second question: "More resilient than *what*?". Typically it is assumed that we mean "more resilient than a centralized grid", but it is important to note that there are several ways in which the centralized grid can be made more reliable and resilient, and any cost-benefit analysis applied to the more distributed system must include these options for the centralized grid. This Part of this paper explores two options for hardening distribution systems that provide resilience against longer-term and more widespread outages.

In this discussion, reference will be made to a number of metrics that are used to quantify the reliability of power systems. These metrics are defined and further described in Reference [10].

2.1. Undergrounding

Distribution systems can be hardened to provide greater immunity to damage during severe weather. In particular, moving overhead lines underground ("undergrounding") can provide major resilience and reliability benefits. Overhead distribution lines, even when insulated (which they typically are not), can be knocked down by wind, trees, and local events like vehicle-pole collisions [47]. Vegetation management ("tree trimming") is often the single biggest item in distribution system maintenance budgets [47]. Underground lines are far less vulnerable to these factors, and as a result, underground distribution lines typically have better reliability index values than overhead lines [40, 41]. In one example in a heavily-forested area, the utility indicated that they had achieved a 97% reduction in customer outage minutes by replacing overhead circuits with underground ones [42]. Underground lines have the added benefit of being an effective way to mitigate wildfires sparked by power systems.

In spite of these advantages, much of the distribution circuit-miles in North America, especially in rural areas, are of overhead construction, because underground construction costs much more than overhead—in some cases by a factor of 3× to 5× [43]. Also, underground lines are not *always* less vulnerable than overhead; for example, underground lines are more vulnerable than overhead lines to flooding and possibly to earthquakes [40], and cutting of underground lines during excavation (so-called 'backhoe attacks') is a problem [47]. Also, while underground lines have a significantly lower outage *frequency* than overhead lines, the outage *duration* can actually be higher for underground than overhead because it takes longer to locate faults and other problems in an underground circuit [47].

Thus, undergrounding is *usually* beneficial, but there may be circumstances in which overhead construction remains the right choice for resilience. In these cases, insulated cables could be considered to reduce exposure of overhead lines to tree contact and momentary contact of conductors in high winds. Insulated cables will also provide at least some wildfire-mitigation benefits [99,100].

In summation, there is still considerable reliability and resilience improvement that can be gained by continuing the existing trend of moving overhead distribution circuits underground.

2.2. Alternate sources and distribution automation

Around 80% [38] to 85% [48] of customer interruptions of electric power service are caused by a problem in the distribution system. This is not surprising since nearly all distribution in North

America is radial, meaning that there is one path from the grid source to each load (and it also typically means that the circuit has only one source [39]). Every element of such a radial circuit—every busbar, switch, fuse, conductor and splice—represents a single point of failure.

One way of improving resilience in a system like this focuses on using distributed energy resources that are close to loads, thereby providing another source that is not subject to at least some of the single points of failure. However, it is also possible to eliminate single points of failure by providing an alternative path to the larger grid via connections to secondary distribution sources [87]. In radial distribution systems, this is typically achieved via the use of sectionalizers, distribution automation, and normally-open (NO) tie lines between adjacent circuits, to achieve a function often called Fault Location, Isolation, and Service Restoration (FLISR). In a typical FLISR scheme, relays communicate with one another so that the last relay upstream from the fault (the last one to see the fault current) and the first relay downstream from the fault (the first one that does NOT see the fault current) open their breakers, isolating the fault into a 'faulted zone' between those two breakers. Then service can be restored by closing the NO tie line, which energizes the section of the faulted feeder downstream from the faulted zone.

Figure 3 on page 7 of this document shows a system equipped with two NO tie lines indicated by dashed lines between the two distribution circuits shown. Figure 3 shows each tie line as having two NO breakers, one at each end (indicated by the green boxes), but a tie line can have only a single breaker.

It has been conclusively demonstrated that this type of distribution automation improves critical system reliability metrics [44-46,49]. However, these studies have typically looked only at local events such as circuit faults. A widespread event such as a hurricane or ice storm might simultaneously knock out parts of the distribution system and the transmission sources to both primary and secondary distribution sources. Resilience to this type of situation could be improved in a system that has both distributed energy resources *and* multiple paths through the distribution system [87], which is the configuration shown in Figure 3.

2.3. Does hardening of distribution reduce the need for DERs or backup power for resilience?

Deployment of the techniques described above would improve the reliability of electric power service to customers, even if no DERs, backup power, or microgrids were deployed. This could reduce the financial incentive for deployment of decentralized electric power sources. However, there is evidence that the frequency of major outages arising at the transmission level is presently rising, primarily due to changes in the severity of weather events [102]. There is thus still justification for locating sources closer to loads for resilience improvement.

3. THE BENEFITS OF SHARING RESOURCES

A key factor that might drive toward a compromise between distributed and centralized architectures is that sharing of resources leads to much lower overall costs and enhanced load-carrying potential.

Individual facility loads tend to be highly variable, or "spiky", and the ratio of the maximum to minimum load can be quite high, noting that the minimum load can be very close to zero. Figure 4 and Figure 5 show two examples of measured load data for two adjacent residences, measured at 1-second resolution [51], for a period of one day. These two examples illustrate the properties just described: the load profile contains primarily stepwise changes in demand, is punctuated by brief spikes of magnitude 500-1000 W that last for 30-60 seconds, and has a minimum of on the order of 240 W[10]. Thus, a generator that serves only this facility will be subjected to somewhat severe duty. However, loads in separate facilities tend not to turn on and off at the same times. There generally tends to be some correlation over longer periods of time, but over short time periods, geographically-adjacent loads tend to be uncorrelated [50]. For example, the characteristics of the load in Figure 5 are similar to those of the load in Figure 4, but the peaks and "spikes" tend not to occur at the same times. As a result of this lack of correlation between individual loads, the *coincident* peak of a group of loads tends to be less than the sum of the individual *noncoincident* load peaks. Figure 6 shows load profiles for a set of 40 individual loads from this same data set [51], and Figure 7 shows the total demand for all 40 of these loads vs. time. For these 40 loads on this day, the sum of their individual peak demands is 180.5 kW, and if one were to specify separate generators for each of these facilities based on these data, the total generation capacity required would have to be at least 180.5 kW[11]. However, when the 40 loads are aggregated (Figure 7), the peak aggregate demand is 62.7 kW, meaning that the generation required to meet this peak is reduced to just over one-third of the total capacity that would be required if each individual facility load has its own generator[11]. Figure 8 shows the sum of noncoincident peaks, and the coincident peak demand of the aggregated load, as a function of number of loads from 1 to 250, again using the data from [51].

This difference between coincident and noncoincident load peaks is quantified using the *diversity factor*, DF, which is defined as

$$DF = \frac{\sum noncoincident\ individual\ load\ peaks}{Peak\ of\ the\ total\ aggregate\ load}$$

Figure 9 shows the diversity factor as a function of number of loads, and Figure 10 shows the coincident (aggregate) peak demand as a percentage of the sum of the noncoincident peaks. Figure 11 is a view of Figure 10 zoomed in on the left-hand side of the x-axis. Figure 11 makes clear that for the data in [51], there is a large reduction in the ratio of the coincident to noncoincident peaks as one increases from one load to six. Beyond six loads, as shown in Figure 10, the ratio of coincident to noncoincident peaks continues to drop, at a much slower rate.

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[10] The measured load actually drops to zero for two nine-second periods during this example day, but it is not completely clear whether these are actual measurements of zero or missing data points.

[11] There would, of course, need to be engineering margins added to this; one does not design generation to be *exactly* equal to the peak load. However, the primary point is the same: if one had to design generation to meet the noncoincident peak demand of each individual facility load, the total nameplate capacity required would be far larger than if one were designing to meet the aggregate load and coincident peak.

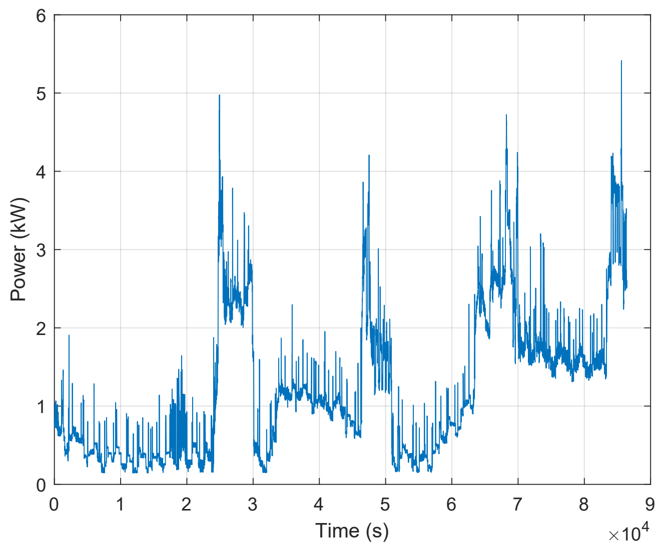

Figure 4. Measured active power demand for a single residence, for one day. Data from [51]. Peak = 5.39 kW.

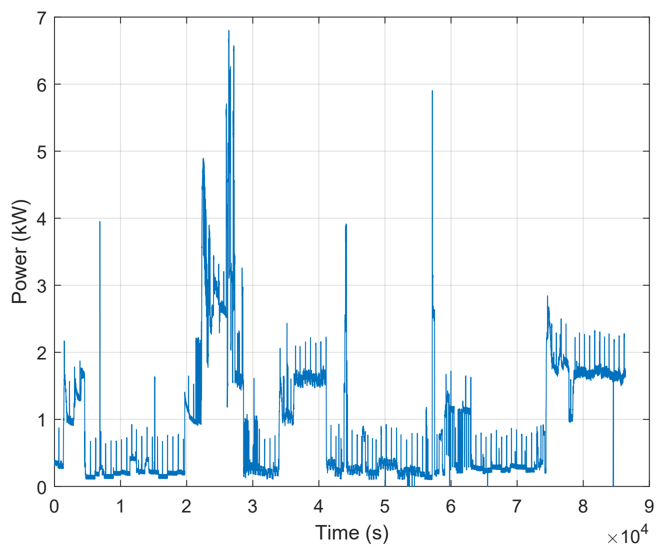

Figure 5. Load profile from an example day for a different single residence geographically close to the one shown in Figure 4. Data from [51]. Peak = 6.80 kW.

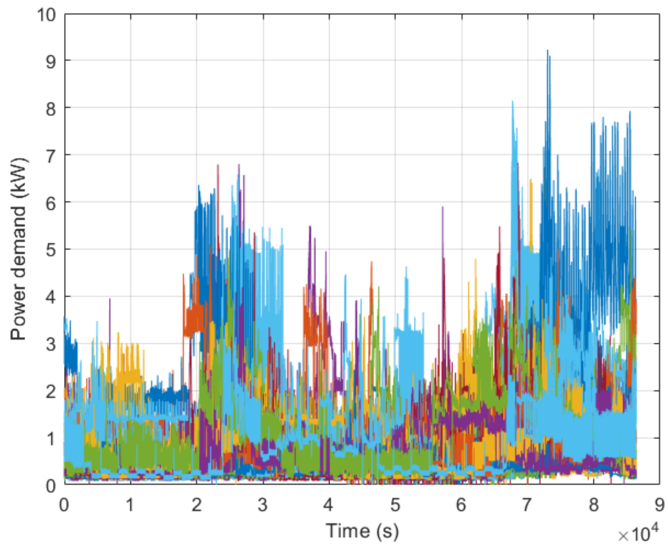

Figure 6. Power vs time for 40 individual facility loads. Sum of individual maxima = 180.5 kW. Data from [51].

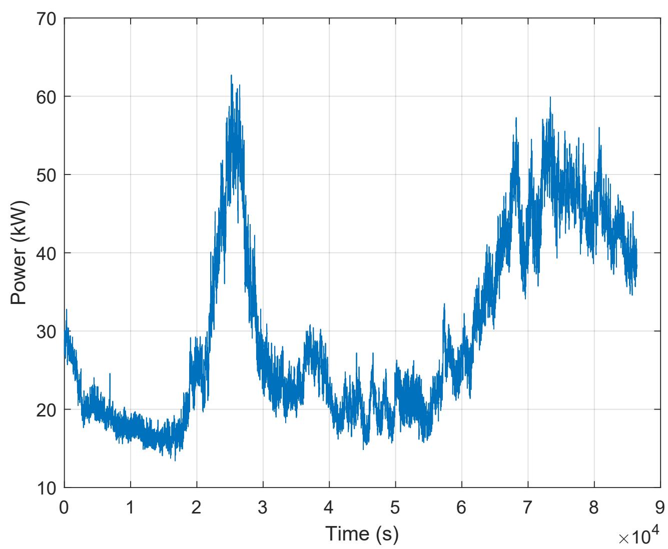

Figure 7. Total aggregate load presented by the 40 loads in Figure 6. Peak is 62.7 kW. Data from [51].

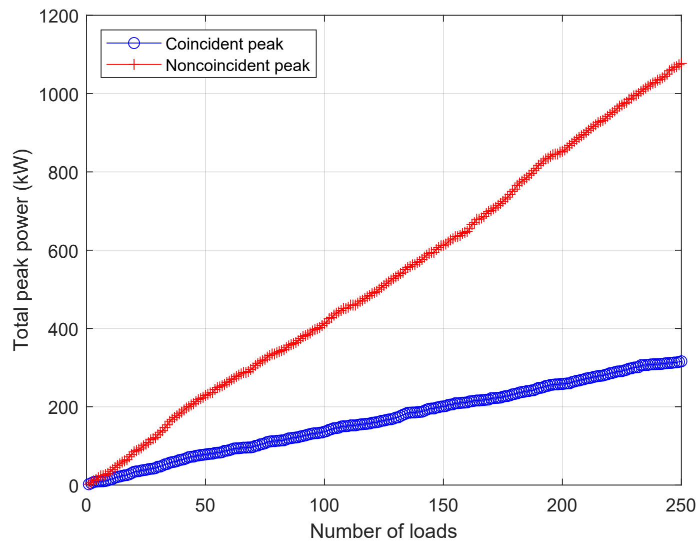

Figure 8. Sum of noncoincident demand peaks (red) and the total coincident load demand peak (blue) as a function of number of loads. Data from [51].

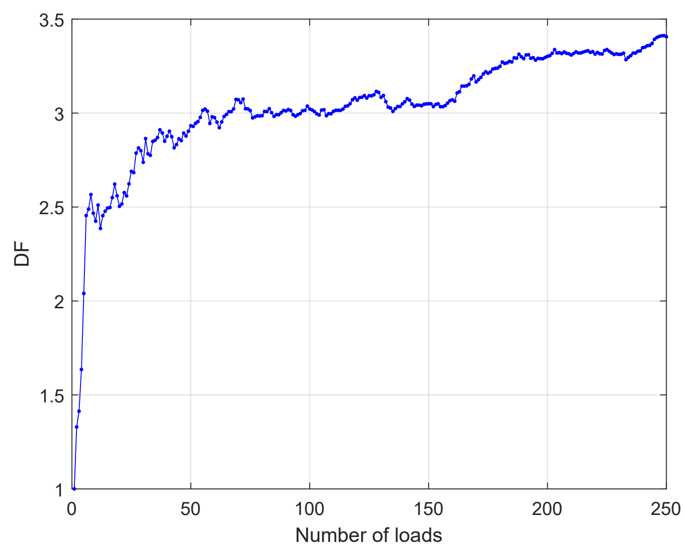

Figure 9. Diversity factors for the data shown in Figure 8. Data from [51].

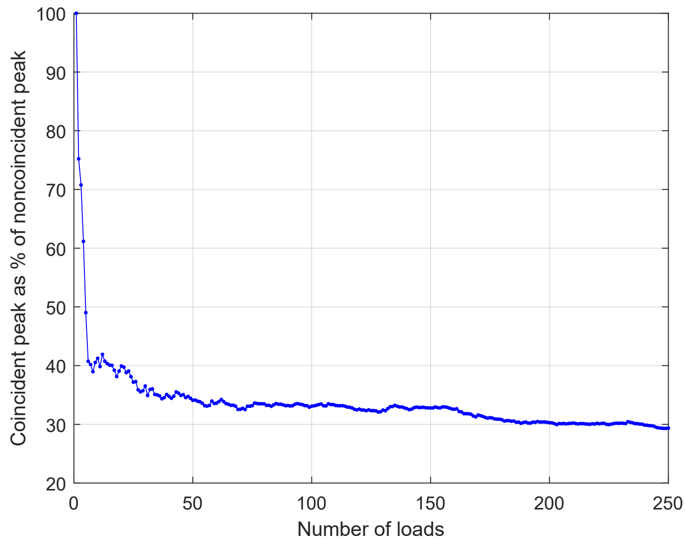

Figure 10. The coincident (aggregate) peak load demand as a percentage of the noncoincident peak demand, as a function of number of loads, for the data in Figure 8. Data from [51].

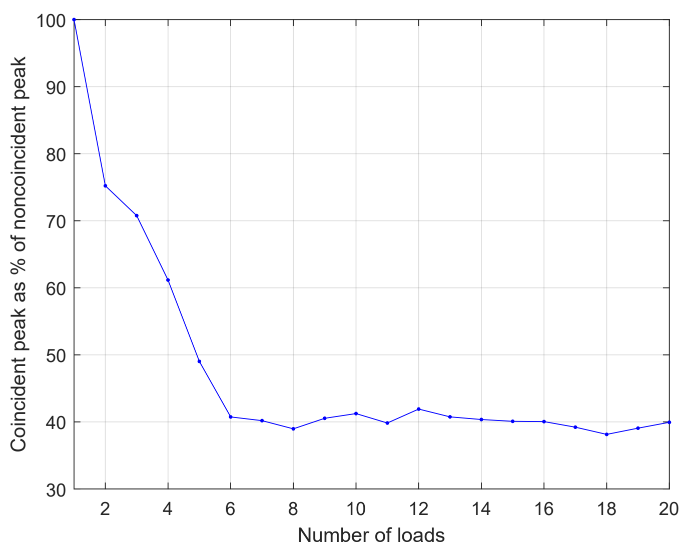

Figure 11. Same data as Figure 10, zoomed in on the low end of the x range. Data from [51].

As discussed above, this means that if one were to design a microgrid serving these loads, the total generation capacity required to serve the load would drop by on the order of one-half if the loads are served in groups of at least six, instead of serving each load individually.

4. CONCLUSIONS

The key conclusions of this paper are as follows.

- Maintenance of centralized machines could potentially be less expensive and easier to do more frequently, providing a driver toward centralization, possibly at the substation or community level. However, this consideration may provide only a weak push toward higher centralization, because most manufacturers and vendors of distributed rotating generators offer service contracts to help keep them maintained, and modern controllers automate certain functions such as periodic 'exercising' of the generators that helps keep them in better condition and alert owners to issues before a resilience event.
- Fuel maintenance requirements (i.e., how long a fuel's storage life is) and fuel delivery models could be mild drivers toward centralization in some cases.
    - Diesel fuel has a number of deterioration mechanisms, and deteriorated fuel can reduce a generator's ability to be reliable and to carry load during resilience events. Therefore, diesel fuel must be kept fresh, and this 'fuel maintenance' could potentially be easier and less expensive for centralized generators. Other fuels, such as propane, have very long storage lifetimes and might be more suitable for highly distributed applications.
    - Diesel and propane are typically delivered by truck, and deliveries by truck may be disrupted during severe events. This might provide a weak driver for centralizing the generators in a single location to which truck deliveries can be made more reliable. In contrast, natural gas is typically delivered by pipeline and thus does not have 'fuel maintenance' requirements or the constraints of being delivered by truck. However, because natural gas it is not typically stored on-site, the resilience of natural gas-powered generators is dependent on the resilience of the natural gas delivery system.
    - There are several promising alternative fuels that offer long storage lifetimes and other sustainability and safety attributes.
- In large-scale disasters or similar events, photovoltaic and wind generation can provide immunity from fuel supply disruptions, which could theoretically allow them to sustain off-grid power systems nearly indefinitely if their loads are appropriately managed. However, their low energy and power densities make it difficult to site sufficient solar and wind near critical loads to keep those loads fully powered during a contingency event. Larger solar and wind fractions can be accommodated if the solar and wind are located where space is available, which provides a significant driver toward centralization. Furthermore, maintenance of PV and wind plants that maintains their readiness to participate in provision of resilience services greatly benefits from extensive monitoring of these plants, including quantitative comparisons against expected production, and this type of maintenance is more easily and economically done on larger, more centralized plants.
- The key factor driving centralization vs decentralization of battery energy storage is likely to be safety. Lithium-ion batteries have minimal maintenance requirements, which would make them well-suited for collocation with loads. However, lithium battery fires, while very rare, do occur. When they do, they burn very hot, emit toxic gases, and can be difficult to extinguish. This *might* provide some driver toward greater centralization, locating the storage away from occupied areas.
- The resilience of the centralized grid is a 'moving target' because of at least two means for improving reliability and resilience that have improving cost effectiveness and that have not yet been fully deployed:

    - Undergrounding of distribution undoubtedly decreases the frequency of outages, and thus increases reliability. There is a tradeoff, though, because undergrounding tends to decrease the outage *frequency* but increase the outage *duration*. Also, in some locations (e.g., those prone to flooding), undergrounding might not always increase reliability. (As noted above, insulated or covered conductors also can contribute to distribution system reliability improvement, but this option has its largest impact on momentary outages, which are of lesser importance to the discussion here.)
    - Sectionalizers, normally-open tie lines between distribution circuits, and distribution automation have major potential for increasing distribution system reliability and resilience. These techniques can work with distributed energy resources to create robust resilient microgrids. However, in very rural areas, providing an alternate source via an adjacent circuit is not always feasible (i.e., in rural areas the adjacent circuit is so far away that providing a tie to it is uneconomical or technically unfeasible for voltage drop reasons).
- It is much less expensive in total if distribution and sources are configured so that sources can share loads during contingency events. Because of load diversity, the total amount of generation required to meet the load demand is much less when resources are shared than is the case if each facility has its own generation. This factor provides a strong economic driver toward centralization.

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