Availability Evaluation of a Nuclear-Enabled Microgrid for a Data Center

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Abstract: Information and data technology is booming, and the global demand for data centers is growing rapidly as their services are integrating with nearly every aspect of modern society. This growth is outpacing the supply of available power from the standard electric utility grid, creating significant challenges for grid operators, including regional constraints on capacity and long lead times for establishing new connections. In the presence of these growing challenges and uncertainty from the utility grid, many are considering alternate sources, such as localized microgrids. A central consideration in designing such microgrids is the balance between reliability, availability, and cost. Through its emphasis on reliability metrics, the nuclear industry has developed a reputation for safety and performance and is a top-candidate power source for data centers.

This work investigates the capabilities of a representative nuclear-enabled microgrid for supplying power to a data center. Generation risk assessment (GRA) with fault tree analysis is employed to evaluate the microgrid operation by estimating the probability and duration for a generator availability due to unanticipated failures and anticipated maintenance downtimes. GRA offers a pathway for comparing microgrid configurations and identifying effective microgrid designs capable of meeting data center availability targets. The output of GRA provides reasonable size and capacity constraints for the microgrid power generators. Ultimately, this work provides inputs and considerations for conducting GRA of nuclear-enabled microgrids and offers a reliability basis for future technoeconomic assessments of data centers.

1. INTRODUCTION

The role of data centers is expanding rapidly across all industries as they support a wide range of customers and operations. As dependence grows, it becomes essential for data centers to deliver highly reliable, nearly uninterrupted service. To achieve their service objectives, data centers require steady reliable sources of electricity. The increased demand for electricity from so many data centers is resulting in long interconnection times [1]. As a result, data center developers are increasingly relying on onsite generation to meet demand. A recent study by Cleanview tracked planned data center projects and found that many data center projects announced in 2025 plan to implement their own "behind-the-meter" approach for electricity [2], nuclear power being seen as an attractive, reliable source of power [3].

Generation risk assessment (GRA) is used to evaluate the risk of generation loss during an operation by estimating the probability and duration for a generator trip or derate due to unanticipated failures and anticipated maintenance downtimes [4]. GRA provides valuable insights for designing, planning, and improving systems or ensuring steady, uninterrupted power from an electrical grid. The steady, and continued uptime or operation of a data center is a central focus especially for critical data centers. GRA techniques pathway for electing "behind-the-meter" or microgrids configurations for data centers. Ramabhotla et al. employed fault-tree analysis to evaluate a microgrid under grid-connected operation [5]. Likewise, Akula and Salehfar also employed fault tree analysis for the assessment of a microgrid. In 2020, Doyle et al. [6] employed probabilistic analysis for nuclear enabled microgrids which was followed by a refined, fault-tree based assessment by Doyle [7] in 2022. The results of both [6] and [7] indicate that nuclear power needs backup power for achieving high availability.

This work presents fault-tree based analysis of a representative nuclear-enabled microgrid for supplying power to a data center. As recently as 2025, attempts have been made to co-locate data centers with nuclear power plants [8]. A Reuters news article states that the Federal Energy Regulatory Commission set a limit of 300 MWe for an agreement between the Susquehanna nuclear power plant and an Amazon data center [8]. The FERC set a power cap citing concerns for reliability and costs from redirecting more than 300 MWe to a single customer. This work establishes a custom case study based on this real-world scenario (i.e., a nuclear reactor providing power to a local data center). The key difference between this work and existing literature is the configuration of the microgrid's power sources. For this work, the microgrid is configured with a full-scale nuclear power plant and natural gas turbines as backup power sources.

2. METHODOLOGY

This work evaluates generation risk using a fault tree to determine the probability of successfully meeting the electrical load of a data center. An average unavailability is captured from two perspectives, 1) the probability that the generation source will be unavailable due to random failures of the generation source during an operational period 2) the probability that the generation source will be unavailable due to scheduled maintenance during the operation period. The combined influence of these perspectives can be interpreted as an expression for average availability of the microgrid. Figure 1 shows the general fault tree configuration for this approach.

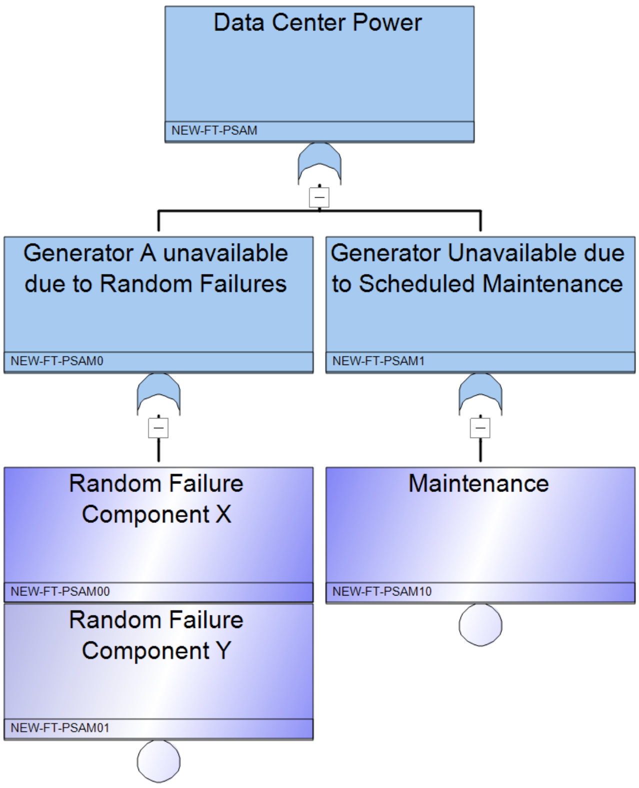

Figure 1. Fault Tree Structure Example for GRA

Procedure:

1. Identify required load of the datacenter
2. Identify generators of the microgrid
3. Determine the failure frequency of the power generator
4. Determine the maintenance frequency of the power generator
5. Construct the fault tree
6. Evaluate the minimal cut sets and top event probability

3. CASE STUDY

This work examines power source average availability for a 300 MWe Data Center. The power supply for the data center is from an islanded local microgrid powered by a nuclear power plant and gas turbine generators, as shown in Figure 2. The nuclear power plant is a 1000 MWe representative light-water reactor, while the natural gas turbine generator is based on aeroderivative gas turbines with a net power output of 52 MWe. All other aspects of the microgrid such as transformers, distribution equipment, etc. are excluded for convenience.

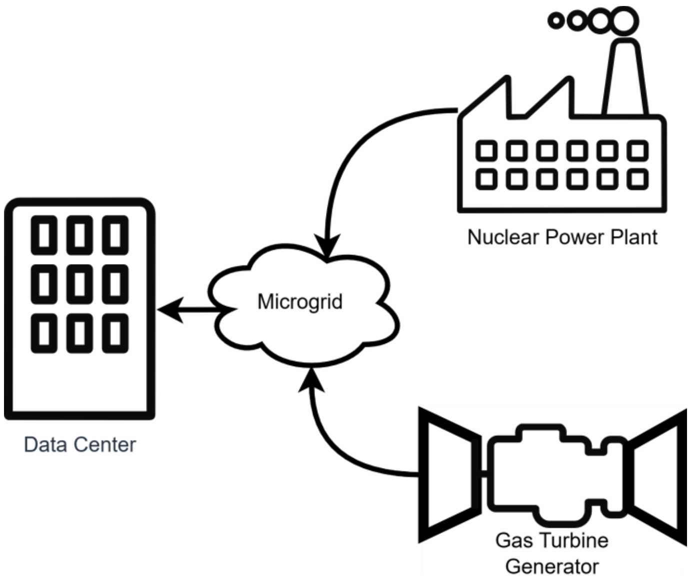

Figure 2. Microgrid Configuration

3.1 Nuclear LWR Data

Nuclear power plant generator data is complex, given they are massive machines with numerous parts. To provide a means of evaluating the reliability and availability of a nuclear power generator, it is necessary to consider the multiple ways by which a reactor may be offline. Presently, advanced and next-generation reactor data is limited. However, data on existing and historical large-scale reactors is more readily available. Table 1 provides data that will be considered for use in a GRA. This work considers failure of the reactor as time during which it is offline or "tripped." This work employs NRC data acquired from current and historical nuclear reactor operations to determine an overall unscheduled trip rate[9] [10]. Table 1 shows this data. Note that the mean duration data was extracted from [6] and [10].

Table 1. Nuclear Power Plant Transient Data.

Initiating Event	Mean event Frequency (per year)	Mean Duration (hours)	Mean downtime (hours)
Loss of vital AC bus (LOAC)	5.29E-03	192.00	1.02
Loss of vital DC bus (LODC)	6.23E-04	120.00	0.07
Partial loss of component cooling water (LCFW)	1.56E-03	348.00	0.54
Loss of feedwater (LFW)	6.98E-02	188.16	13.13
Partial loss of service water (LSW)	1.25E-03	408.00	0.51
PWR loss of instrument air (LOIA)	8.44E-03	59.04	0.50
PWR loss of heat sink (LOHS)	5.81E-02	340.80	19.80

Initiating Event	Mean event Frequency (per year)		Mean Duration (hours)	Mean downtime (hours)
PWR General Transient (GT)	9.43E-01		137.52	129.68
Loss of coolant accident (LOCA)	1.56E-03		1200.00	1.87
Loss of offsite power (LOOP)	2.36E-02		18.11	0.46
Total events/year		1.1132		
Total event down time per year (hours)		167.56		

Traditional light water reactors typically need to shut down and refuel every 18 to 24 months of operation for PWR and BWR, respectively. For PWRs, researchers have been exploring the potential upgrades of fuel cycle length to 24 months [11]. The upgrade of BWR fuel cycle to 36 months is still in a research stage. During the refuel outages, the NPP will conduct preventive or corrective maintenance to ensure the best performance of its systems. The U.S. EIA publishes information on the average length of refueling outages for operating plants in the U.S. based on information from the Nuclear Regulatory Commission (NRC) [12]. The average length of refueling outage for plants in a given year ranged from approximately 30 days to 45 days between 2000 and 2023 [12]. However, refueling outage length can vary by plant. For example, Constellation has reported that the average refueling outage length for its fleet averaged 21.5 days in 2025, compared to the industry-wide average of approximately 37.5 days [13].

3.2 Natural Gas Turbine Data

The IEEE gold book provides some data to support availability and reliability analysis of natural gas turbine generators [14]. Some of this data is shown in Table 2. Both are for continuous (i.e., data is for failures while running) more commonly known as "failure to run" modes of failure. Note that MTBF is the mean time between failures, MTTR is the mean time to repair, MTTM is the mean time to maintain, and MDT is the mean downtime. The information presented in Table 2 is unspecified as to the type of gas turbine. Aeroderivative turbines typically need more frequent maintenance than industrial frame turbines. Despite the longer interval between maintenance, the industrial frame models have a longer downtime for their maintenance activities [15].

Table 2. Gas Turbine Reliability Data.

Class	Unit-years	Failures	Failure rate (failures/year)	MTBF	MTTR	MTTM	MDT
750 kW-7 MW *	167.9	290	1.7276	5070.6	27.39	1	1.225
*Packaged gas turbine generator							

Table 3. Gas Turbine Maintenance of NGTs.

NGT maintenance (Aero)	interval (hours)	Mean time to perform*		hours/year
Borescope Inspection	4000*	12		26.28
Hot Section Combustor Rotator Exchange	25000**	72		25.23
Major overhaul Core Exchange	50000**	48		8.41
		Total mean hours/year	59.92	
		Maintenance probability	6.840E-03	
*[16], **[17]				

3.3 Results

The data shown in the previous section was used to evaluate the probability that the power generators will be unavailable due to random failures and scheduled maintenance during the operation period of one year. Table 4 shows the results.

Table 4. Model Inputs and Reasoning.

Model inputs	Values	Importance and assumptions
Failure rate of the NPP (per hour)	1.271E-04	Drives unavailability due to random failures (based on data from Table 1)
Maintenance probability of the NPP	6.895E-02	Drives unavailability due to scheduled maintenance. Maintenance was calculated from 18 months refueling outage interval and duration of 37.75 days [18]
Repair time for the NPP (hours)	167.59	Influences unavailability due to random failures. Also, the time required for backup load coverage by NGTs Table 1).
Failure rate of the NGTs (per hour)	1.972E-04	Drives unavailability due to random failures (based on Table 2
NGT failure to start (per demand)	1.4E-02	Failure to start based on "starting reliability" given in [19]
Maintenance probability of the NGTs	6.840E-03	Drives unavailability due to scheduled maintenance (value from Table 3)
Repair time for the NGTs (hours)	27.39	Influences unavailability due to random failures. Also, the time required for backup load coverage by additional NGTs, if available. (value from Table 2**Table 3**)

Five different cases were evaluated, these include nuclear as the only power generation source, and nuclear backed by 6, 7, 8, and 9 NGTs. The resulting probability that the power will be available for the data center based on these cases is shown in Table 5. Meanwhile, Figure 3 plots the growth of availability in response to the introduction of additional backup generation sources.

Table 5. Case Study Results

Case	Scenario	Average availability
1	Nuclear solo	91.297000%
2	Nuclear + 6 NGTs	99.553100%
3	Nuclear + 7 NGTs	99.986660%
4	Nuclear + 8 NGTs	99.999625%
5	Nuclear + 9 NGTs	99.999990%

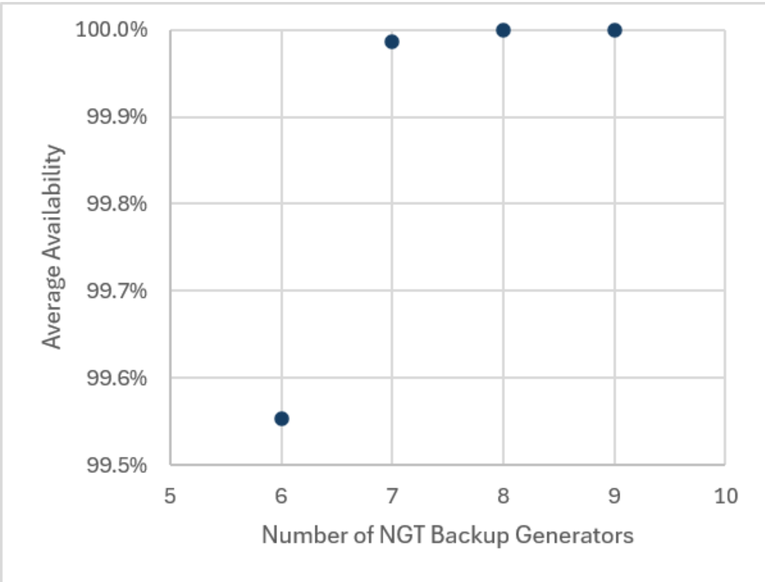

Figure 3. Availability Growth

4. CONCLUSION

In 2020, Doyle et al. evaluated a NuScale 12-module (600MWe) nuclear power plant configuration for a microgrid, showing 99.95% reliability is achieved for 100 MWe [6]. As a comparison with the present study, Doyle et al. found the probability of 300 MWe available was a little better than 99%. This was achieved with a total installed plant rating of 600 MWe and best matches Case 2 from Table 5 (i.e., 300 MWe from the NPP and approximately 300 MWe as backup NGTs). Later, Doyle calculated much higher values over five 9s [7]. It should be noted that such high availability values can be attributed to redundancy in components and generators of the microgrid.

Table 5 shows that five 9s is achievable with an existing large NPP so long as there is sufficient backup power to cover the long downtimes associated with the refueling outages of the large NPP. One potential downside to the proposed configuration (i.e., large NPP as the primary power source) is that the maintenance/refueling operations for the large NPP completely halts all power for a data center; thus, the only way to ensure nearly continuous operation of the data center is to have completely redundant and for the data center during the NPP outage. The benefit of next generation NPPs is the potential for online refueling, longer periods between downtimes, and modular configurations. Shorter downtimes increase availability, while modular configurations (e.g., one bonus module over the minimum required to cover the data center load) allow maintenance while still providing complete load coverage. Future work will expand and leverage the present study to support technoeconomic assessments of powering datacenters.

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