Dynamic Generation Risk Assessment of Modular HTGR for Integrated Energy Systems

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Abstract: This work develops and applies a dynamic Generation Risk Assessment (GRA) framework to quantify the ability of a modular high temperature gas cooled reactor (MHTGR) system to satisfy a high temperature electrolysis facility's (HTEF's) steam and electrical demands. The methodology extends conventional probabilistic risk assessment by explicitly modeling demand based performance metrics, non safety derates, safety related reactor trips, common cause failures, and dynamic dependencies. Individual MHTGR subsystems—such as the helium purification system, reactor plant cooling water system, main circulators, steam generators, turbine generator auxiliaries, and electrical distribution components—are parameterized using subsystem level failure and repair models with associated MTBF, MTTR, and derate relationships.

The analysis employs Event Modeling Risk Assessment using Linked Diagrams (EMRALD) dynamic PRA to capture state dependent transitions, time varying interactions, and maintenance driven outages. This includes explicit modeling of startup transients, staggered periodic maintenance, turbine cumulative versus non cumulative derates, and reactor/turbine capacity under varying failure states.

Results show that the baseline four pack MHTGR configuration exhibits no redundancy, causing generation reliability to fall sharply whenever any reactor or turbine is unavailable. Decomposition of unreliability factors indicates that periodic maintenance and random subsystem failures dominate generation unreliability. Sensitivity studies were performed to assess how results vary under different assumptions, including alternative turbine derate logic, and increased redundancy up to two four packs of MHTGR. An additional analysis evaluates the tradeoffs between overbuilding reactor units and supplementing power supply from the grid.

Comparisons with static PRA using Systems Analysis Programs for Hands on Integrated Reliability Evaluations (SAPHIRE) show agreement in results and highlight complementary insights: dynamic GRA captures time dependent dependencies and variations in power output, while static PRA more effectively captures extremely low probability events but lacks temporal fidelity. Collectively, the work demonstrates that dynamic PRA provides essential insights for integrated energy system (IES) design, revealing reliability constraints, key failure contributors, and trade offs between redundancy, derates, and supplemental grid power.

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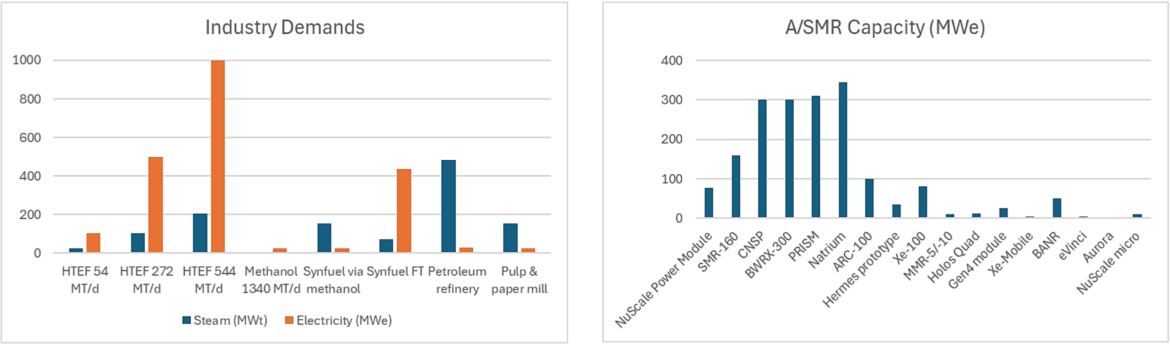
1. INTRODUCTION

Integrated Energy Systems (IES) that pair advanced/small modular reactors (A/SMRs) with industrial processes—such as hydrogen production, high temperature electrolysis, or chemical manufacturing—require consistent, highly reliable thermal and electrical supply. Conventional Probabilistic Risk Assessment (PRA) focuses on nuclear safety but does not quantify the plant's ability to meet industrial energy demand. To fill this gap, Generation Risk Assessment (GRA) provides a performance measure describing how reliable A/SMRs can supply enough energy to meet industrial needs [1]. This is important especially when the gap between industrial demands and current A/SMR capacities is considered, as shown in Figure 1 which data is taken from [2][3]. The gap begs the question: How many A/SMRs are needed to meet industry demands reliably?



(a) Industry demand (b) A/SMR capacity

Figure 1. Industrial demand versus A/SMR capacity

This paper approaches the question using GRA methodology. There are references and technical guides on GRA implementation yet mostly are focused on a static approach using fault trees and event trees [4][5][6]. We implement a dynamic approach in this study to obtain further insights than what static PRA provides. Dynamic GRA approaches, built on discrete events or state transition modeling, incorporate time dependent behaviors such as maintenance cycles, repair actions, startup transients, demand profiles, and component dependencies. This makes dynamic GRA especially suitable for long term evaluation of modular reactor systems configured for co-generation.

This study assesses the generation reliability of a reference IES configuration which consists of modular high-temperature gas reactor (MHTGR) plant consisting of four reactor (Rx) modules and two turbine generator (TG) sets providing 105 MWt steam and 500 MWe electricity to a high-temperature electrolysis facility (HTEF) [1]. The analysis quantifies how system structure, redundancy, maintenance, and stochastic failures affect long term performance, and it identifies strategies to strengthen energy resilience as the number of reactor modules increases.

2. METHODS

Reliability can be presented in different ways. Sometimes reliability is defined as roughly equivalent to availability. Reliability as analysed in this study is different from availability, which is formulated as:

$$Availability\ Factor = \frac{\sum uptime}{operation\ time} \times 100\% \tag{1}$$

Availability is a component's as-fabricated performance metric that is independent of its case-specific use, while generation reliability is a performance metric that is dependent on a generator's particular use in meeting a certain load requirement, formulated as:

$$Generation\ Reliability = \frac{\sum time_{supply \geq demand}}{\sum demand\ time} \times 100\% \tag{2}$$

Which is also different from the more widely known capacity factor metric formulated as:

$$Capacity\ Factor = \frac{\int power\ generation\ \partial t}{Nameplate\ capacity\ \times\ operation\ time} \times 100\% \tag{3}$$

The reference IES used in this study is illustrated in Figure 2. MHTGR is a paper reactor designed by General Atomics but has never been constructed or operated. Public literature on this reactor is widely available. Some of the MHTGR systems and their corresponding derates to the plant's output capacity are listed in Table 1, while the complete list is available in [7]. A four-pack MHTGR station has a maximum capacity of 1400 MWt or 540 MWe and has an operational life of 40 years.

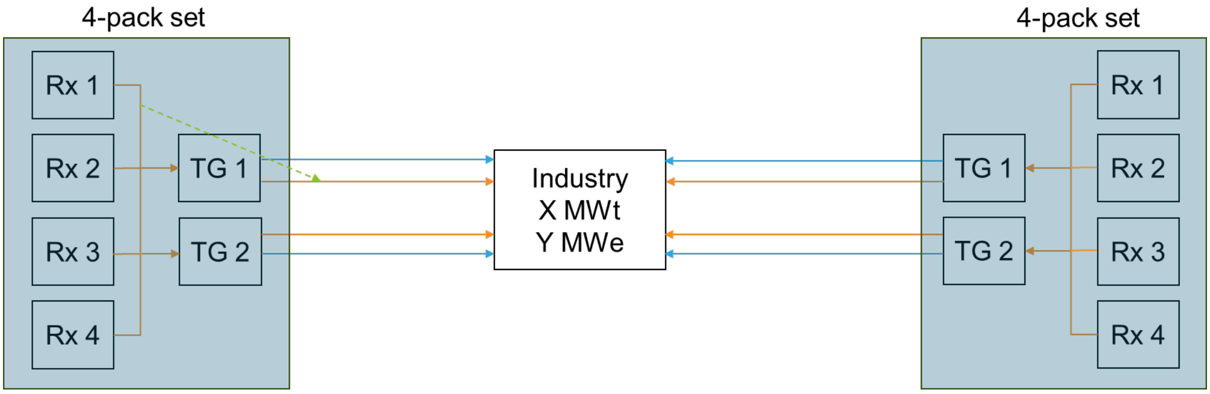


Figure 2. Schematic of reference IES, where Rx refers to reactor and TG refers to turbine generator

Table 1: Example of MHTGR Systems Modelled in GRA

Systems/Operations	Affects	Derates	Quantity per 4-pack
Helium purification system	1 Rx	100%	4
Liquid nitrogen system	2 Rx	100%	2
Reactor plant cooling water system	4 Rx	100%	1
Condenser	1 TG	20%, 100%	2
Instrument and service air system	2 TG	100%	1

2.1. Static GRA

Each of the systems listed in Table 1 is modeled as a basic event in Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (SAPHIRE) software [8], and its associated derate probability is calculated as:

$$Derate\ probability = \frac{\lambda t}{1-\lambda t}\left(1-e^{-\left(\left(\lambda+\frac{1}{\tau}\right)*t\right)}\right), \tag{4}$$

where λ is the system's failure rate, t is mission time, and τ is its mean time to repair (MTTR). Multiplying the derate probability by 8,760 hours gives the number of hours each year that the component will be in a repair state due random failures. This is added to the probability of maintenance times the mean time to maintenance (MTTM) to calculate the system's unavailability:

$$Unavailability = P(Random\ Failure) * t + P(Maintenance) *\ MTTM \tag{5}$$

Fault trees (FTs) are constructed to represent the logical structure of how single train-level system failures combine. In each FT, the top event is defined as a specific derating level, restricted to those derived from combinations of single-train failures. An event tree (ET) is developed to systematically represent the different combinations of system failures that give rise to each derating scenario. Each branch is divided into a success branch, representing cases where derating does not occur, and failure branches, representing cases where derating occurs. The failure branches are further subdivided depending on the number of combinations contributing to the same derate level (e.g., a single occurrence, two simultaneous occurrences, or more).

To attain the data required for the GRA, the model is solved at the ET level, then the end states are gathered and solved for sequence cut sets. The resultant sequence cut sets include a complete set of the derating scenarios. These end states are gathered to determine the frequency of occurrence of each sequence per hour. This is then multiplied by the desired 1-year mission time for the downtime estimate for each derate percentage:

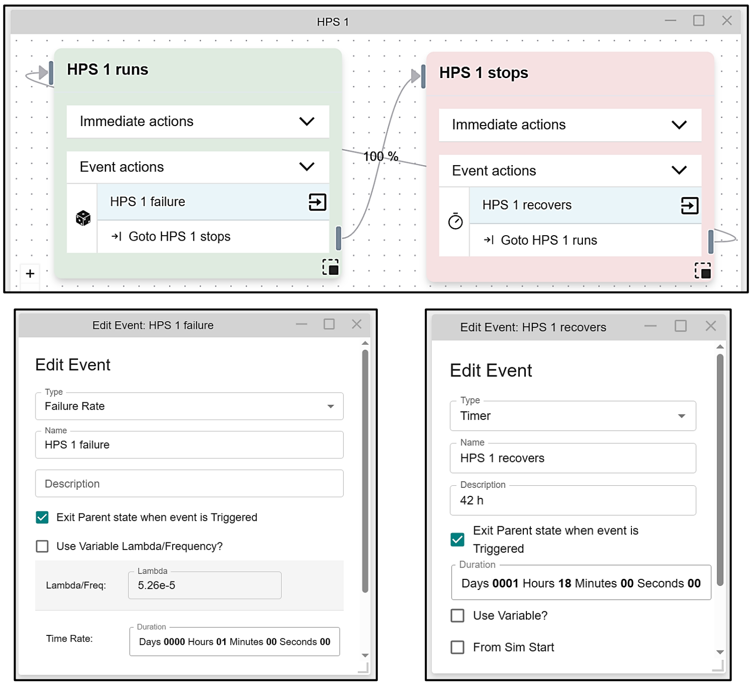
$$Downtime(PCT - Derate) = \sum P(Sequence\ Cut\ Sets) * t \tag{6}$$

Where PCT derate is the end state assigned to a percentage (PCT) derate scenario, sequence cut set is the sequence hourly probability and t is the mission time of 8760 hours.

2.2. Dynamic GRA

The dynamic GRA utilizes the same failure rates for basic events as the static GRA, but it models most of the system in a simulation rather than a logic tree. Since it is a state-based linked model, the MTTR is not used in the determination of derate probability as shown in Equation (4). The MTTR is evaluated when the state changes from running to a failure state instead. Dynamic GRA is performed using Event Modeling Risk Assessment using Linked Diagrams (EMRALD) [9]. Several approaches to modeling MHTGR systems are detailed below:

1. A simple "on or off" model for NSSS with a certain failure rate and time to recover from failures: For example, consider the helium purification system (HPS) shown in Figure 3. The active state is "HPS 1 runs" when HPS 1 runs, and then it transitions to "HPS 1 stops" when HPS 1 experiences a random failure. The active state transitions from "HPS 1 stops" to "HPS 1 runs" again after a certain repair time. The possible capacity changes in this HPS model are from 100% to 0% and from 0% to 100% capacity.



Edit Event

Type: Failure Rate
Name: HPS 1 failure
Description
☑ Exit Parent state when event is Triggered
☐ Use Variable Lambda/Frequency?
Lambda/Freq: Lambda 5.26e-5
Time Rate: Duration Days **0000** Hours **01** Minutes **00** Seconds **00**

Edit Event

Type: Timer
Name: HPS 1 recovers
Description: 42 h
☑ Exit Parent state when event is Triggered
Duration: Days **0001** Hours **18** Minutes **00** Seconds **00**
☐ Use Variable?
☐ From Sim Start

Figure 3. HPS EMRALD model

2. A multicapacity model for the balance-of-plant systems that models the different combinations of derate levels. This model type assumes that repairs from a complete failure state restore the system to its full capacity (100%). For example, the condenser model shown in Figure 4 includes two green operational states and a red non-operational state. The possible capacity changes in this condenser model include the transition from 100% to 80% capacity, 80% to 100%, 80% to 0%, 0% to 100%, or 100% to 0%.

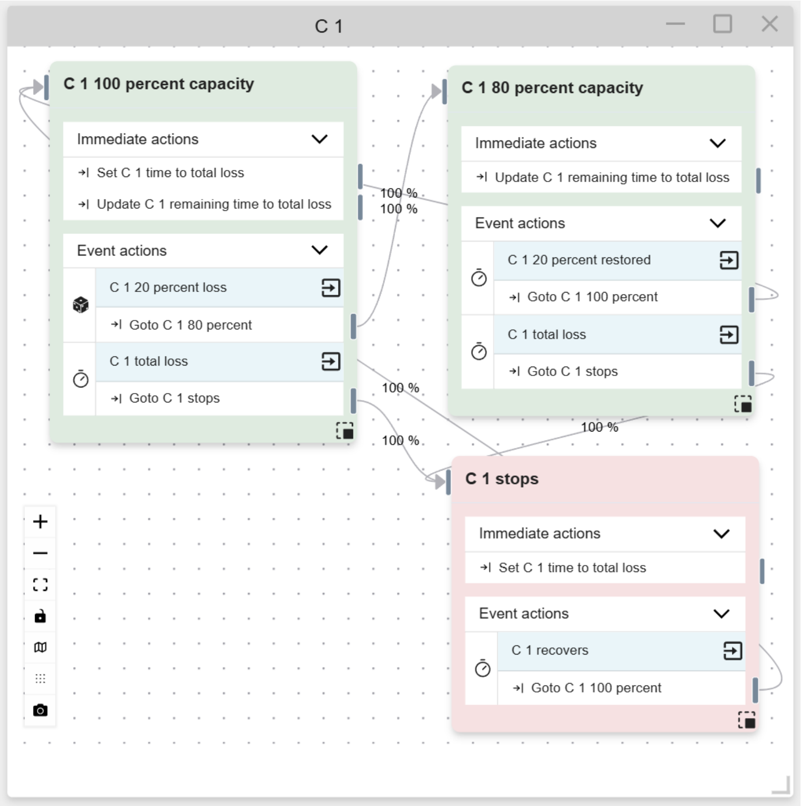


Figure 4. Condenser EMRALD model

3. System dependencies with coping time. For example, helium purification function in the MHTGR design is maintained by two systems, namely the HPS and liquid nitrogen system (LNS). Therefore, an FT is developed in Figure 5 to account for failures of the HPS 1 or the LNS 1 system that cause the loss of helium purification for Reactor 1. However, this functional failure is not immediate. There is a tolerance time of six hours from the failure of any of those two systems until impurities in the helium coolant exceed the allowed threshold level. Therefore, the “HP 1 fails” top event in Figure 5 is used to trigger the “any of He 1 system fails” event in the “He 1 pure” state shown in Figure 6. When this event is triggered, EMRALD enters “He 1 coping time” state to evaluate if all systems are restored within six hours. If systems are repaired within six hours, EMRALD enters “He 1 pure” state; otherwise, it enters the “He 1 impure” state.

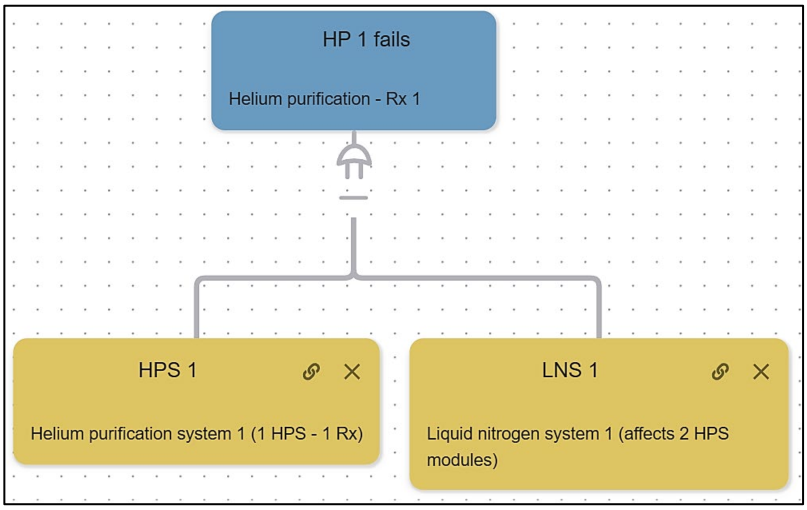


Figure 5. FT of the helium purification function

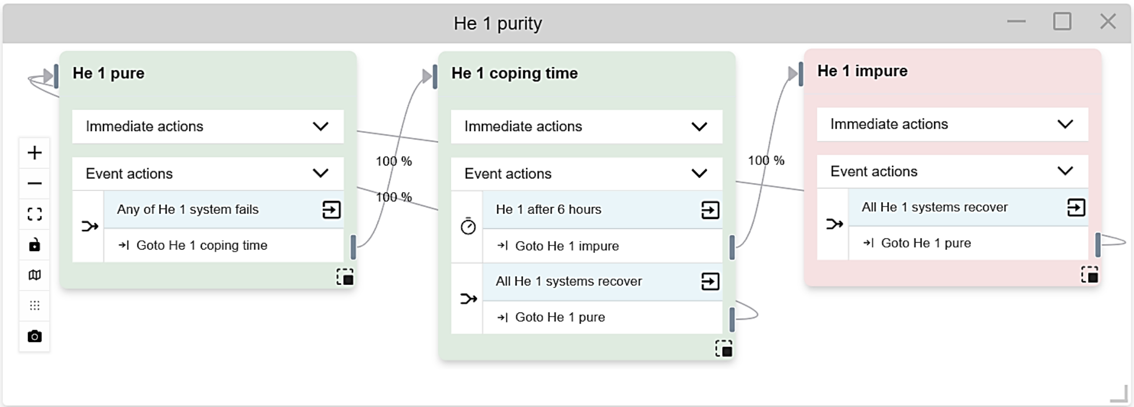


Figure 6. Model of the loss of helium purity for reactor #1 in EMRALD

GRA is performed to answer the following key questions:

- What is generation reliability for varying number of MHTGRs?
- What contributes the most to unreliability?
- How will results change if assumptions change?
- What are the available options to improve reliability?

3. RESULTS AND DISCUSSIONS

Figure 7 and Figure 8 illustrate the time-dependent power output of an MHTGR during its first year of operation, assuming a single four-reactor module supplying steam and electricity to the HTEF. The reactors are started in a staggered sequence at 40-day intervals to support a similarly staggered maintenance strategy, ensuring that no more than one reactor is offline at any given time. Under this arrangement, the station can achieve its maximum electrical output—exceeding HTEF demand (540 MWe > 500 MWe)—after approximately 120 days, while steam demand is met immediately (350 MWt > 105 MWt). However, as shown in Figure 8, a single four-pack station cannot consistently meet the HTEF electrical demand, necessitating a gradual increase in the number of reactors and turbine generators.

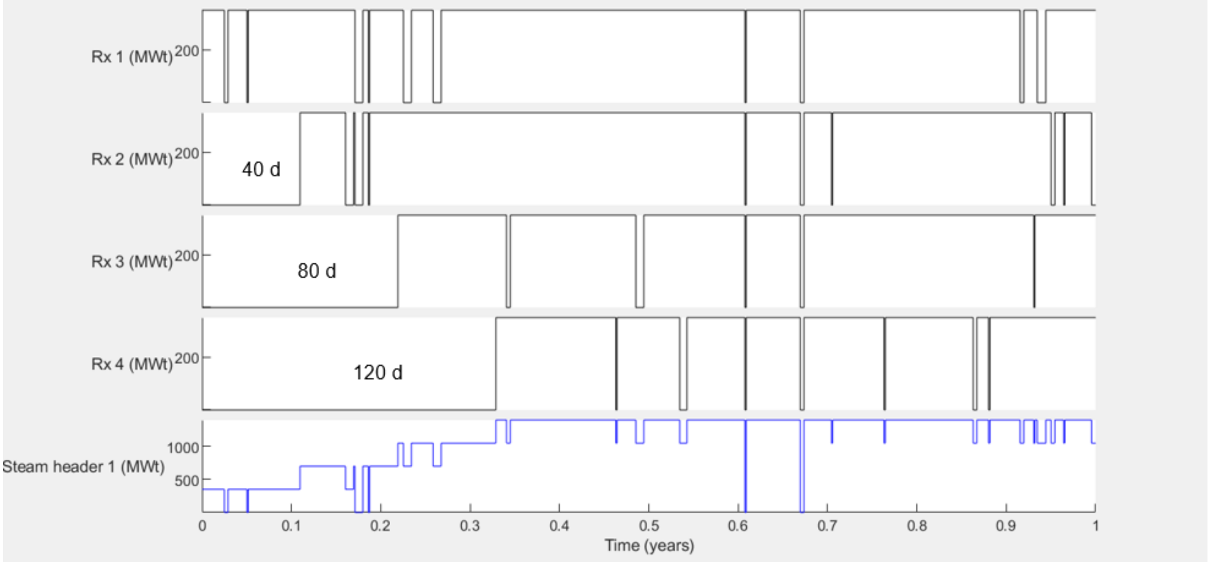


Figure 7. MHTGR steam output during the first year of operation

The resulting generation-reliability metrics are presented in Figure 9. Steam-supply reliability remains consistently high, exceeding 98% across all configurations. In contrast, the reliability of meeting both steam and electrical demands begins at 68.57% for the baseline configuration and increases steadily as additional reactors and turbine generators are added. The uncertainty band associated with these reliability estimates narrows with increasing system size, indicating improved robustness as redundancies are introduced.

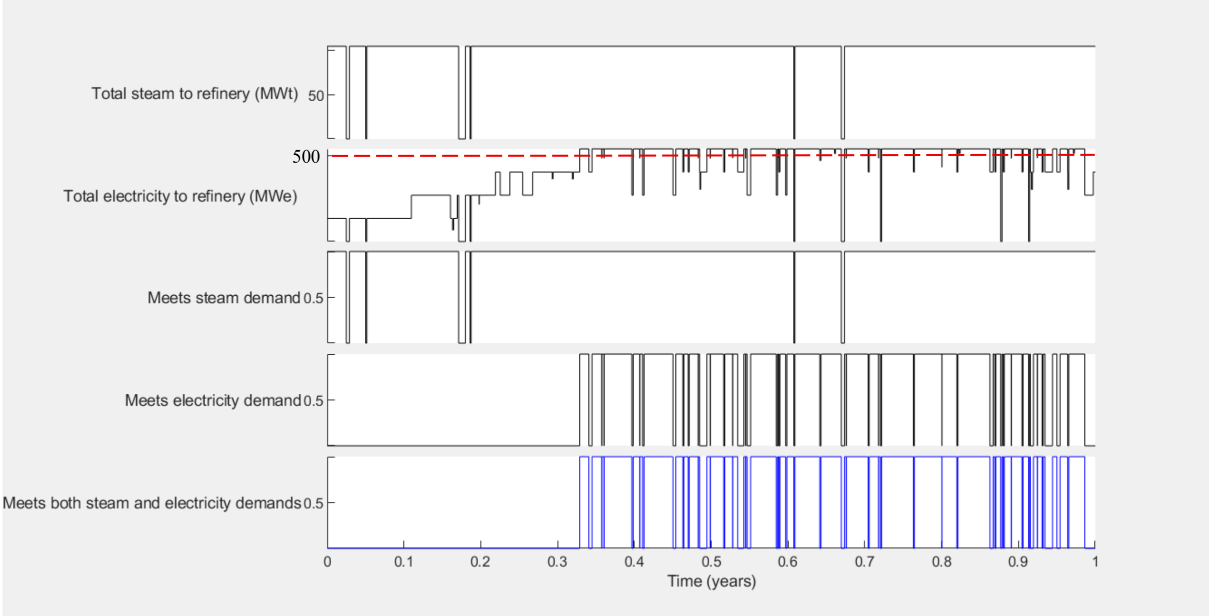


Figure 8. MHTGR output during the first year of operation

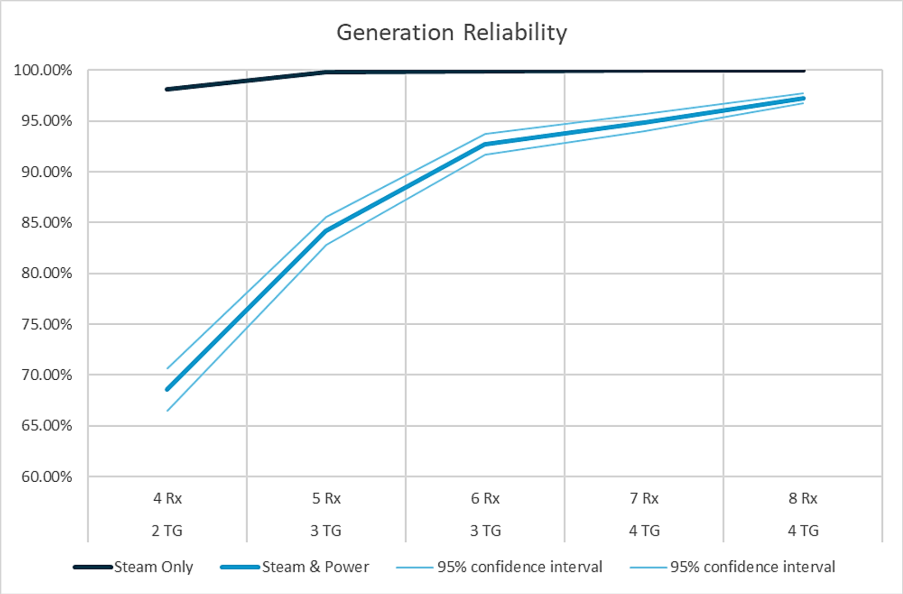


Figure 9. Generation reliability with varying number of reactors and turbine generators.

Figure 10 provides insight into these trends by illustrating the relative contributions of different unreliability factors. For the baseline configuration of four reactors and two turbine generators, periodic maintenance contributes substantially to unreliability because demand cannot be met when any single reactor or turbine is offline. This effect diminishes with increasing redundancy and becomes negligible once the station reaches eight reactors and four turbine generators. Random failures exhibit a similar pattern, contributing significantly to unreliability in smaller configurations but decreasing as redundancy improves, thereby reducing the uncertainty observed in Figure 9. Startup effects contribute the least to unreliability overall, though their influence increases slightly as the number of reactor modules grows, due to the longer staggered startup period required for larger systems.

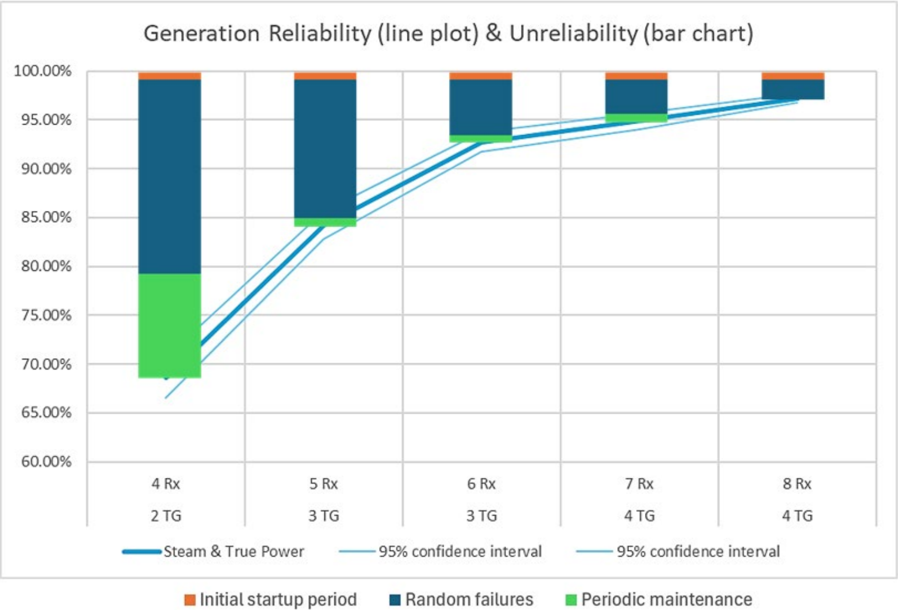


Figure 10. Contributors to unreliability.

Further analysis was conducted to assess the relative importance of MHTGR systems to the power output of a four-pack module. Figure 11 presents system-level reliability along with the associated power-derate magnitudes following system failures. These systems were grouped into three categories reflecting their relative importance. The turbine generator, shown in the red group, is the most critical because it is less reliable than the other systems and its failure results in a substantial 50% derate, owing to the presence of only two turbine generators in the four-pack. Systems in the yellow group are of intermediate importance, either because they exhibit higher reliability or because their failure results in less severe derates. Systems in the green group carry the least importance due to both their higher reliability and the minimal consequences associated with their failure.

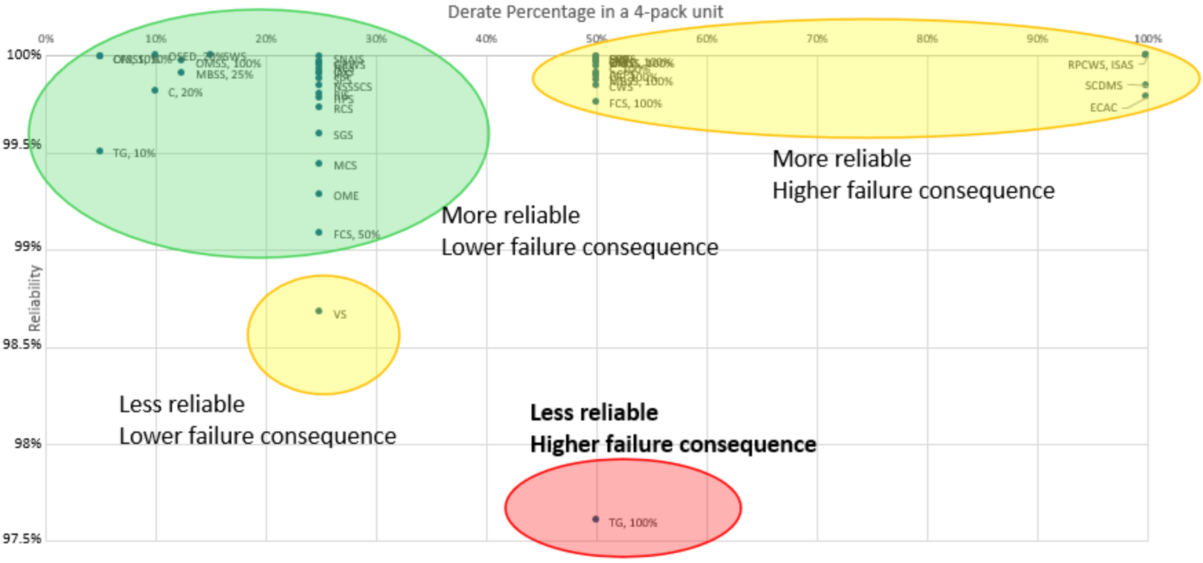


Figure 11. The reliability of MHTGR systems and their impacts on power derates.

The results to this point assume that turbine derates are cumulative, meaning derate magnitudes are additive when multiple systems fail. For example, a condenser fault leads to a 20% derate and a main steam system fault to a 25% derate; if both occur simultaneously, the turbine experiences a total 45% production loss. An alternative assumption is that turbines retain full physical production capability but are intentionally derated by operators to satisfy system safety constraints. Under this assumption, the turbine would be limited to the largest single derate—in this example, 25%. Figure 12 compares reliability estimates developed using these two modeling assumptions.

This comparison indicates that MHTGR generation reliability is largely insensitive to whether turbine derates are treated cumulatively or non-cumulatively. The insensitivity arises because the likelihood of multiple independent derate-causing events occurring simultaneously is extremely low. For instance, the probability of a condenser failure causing a 20% derate is 9×10^{-4}, while the probability of a main steam system failure causing a 25% derate is 2×10^{-3}; the combined probability of both occurring is therefore approximately 2×10^{-6} over the 40-year plant lifetime. One might ask whether the sample size should be increased to roughly one million samples to capture such rare events. The answer is no for two reasons. First, generation reliability is not a safety-related metric; therefore, derate events may be treated statistically without the need to explicitly model or mitigate extremely rare "black-swan" combinations, as determined in the PRA. Second, because derates can be handled as an aggregate performance metric, increasing the sample size to capture rare events would not meaningfully alter the aggregate result.

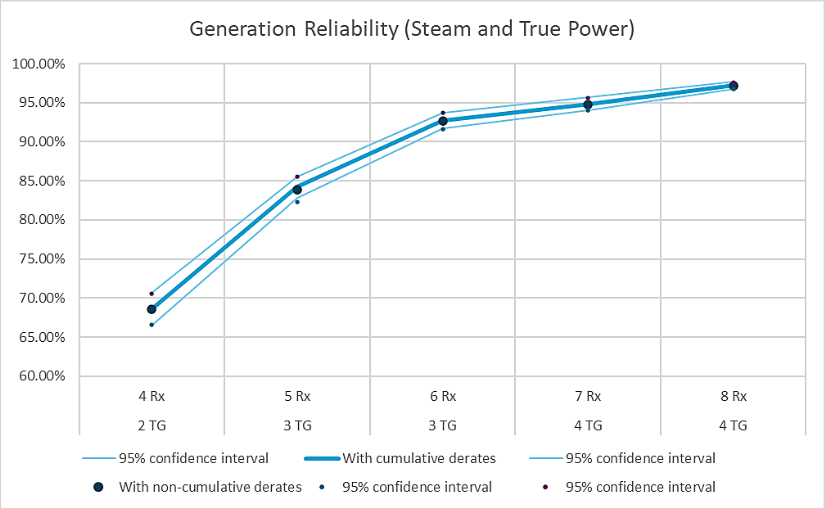


Figure 12. Comparison of generation reliability from cumulative and non-cumulative turbine derates.

After evaluating generation reliability, identifying causes of unreliability, and performing a sensitivity analysis to evaluate various "what-if" scenarios, another question may be asked: How can generation reliability be improved aside from improving redundancies (i.e., overbuilding the reactors)? There are several options that may be considered:

1. Storing surplus electricity to complement supply during plant derates. Figure 13 illustrates that an MHTGR four-pack can produce 40 MWe of excess after meeting the 500-MWe demand. This surplus power can be stored and then discharged to balance the supply-demand gaps.

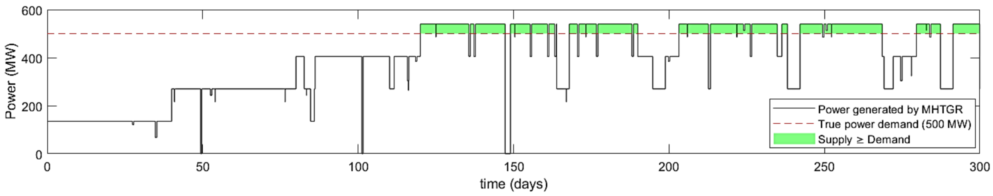


Figure 13. Electricity production timeline. Excess production is highlighted in green.

2. Using peaking plants to complement MHTGR supply during extended outages (e.g. scheduled maintenance). As shown in Figure 14, this extended outage can last several months.

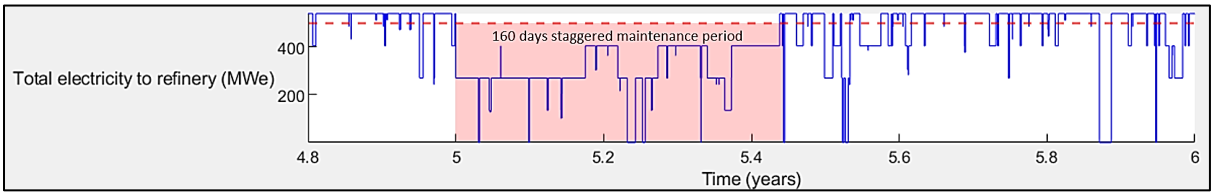


Figure 14. Electricity production timeline. Periodic maintenance period is highlighted in red.

3. Importing power from the electrical grid to complement the MHTGR supply-demand gap. The underlying issue to resolve is that the reliability of MHTGR electricity supply is always lower than the reliability of steam supply. So the question becomes: Should the HTEF stop its operation when steam supply is available but electricity supply from the MHTGR is lacking? If the answer is no, and it is desirable to maintain the HTEF's operation, how much power needs to be supplemented from the grid, and what is the cost? In other words, what does it take to "match" steam supply reliability, or what does it cost to "lift" the blue curve to the black curve shown in Figure 9? Figure 15 answers this question while also inciting a technoeconomic question: Which option is the best business decision, supplementing power from the grid, overbuilding reactors, or a combination of both? Answering this question is reserved for future research.

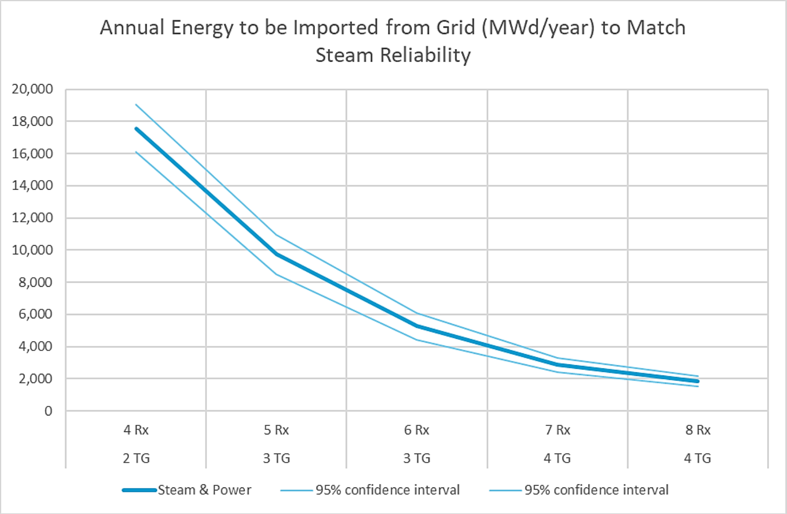


Figure 15. Grid electrical power needed to match MHTGR electricity supply reliability to its steam supply reliability.

Results from the dynamic GRA modeling approach are compared with those from the static GRA approach in Figure 16, which demonstrates strong consistency between the two methods. It should be noted that the current static GRA assessment was conducted only for full 4-pack station increments (i.e., 4-reactor and 8-reactor configurations), rather than the partial increments analyzed using the dynamic GRA. Figure 17 compares the reliability metrics described in Section 2 for a 4-pack MHTGR with the average performance of operating pressurized water reactors (PWRs) in the United States, which data was collected from January 2005 to May 2025 [10]. In terms of capacity factor—the metric most frequently cited for the operating nuclear fleet—the MHTGR exhibits a slightly lower value (86–87%) relative to U.S. PWRs. However, its availability factor is higher, at approximately 97%, compared with the U.S. PWR average of 91.7%. In contrast, the MHTGR's generation reliability in meeting HTEF demand is markedly lower (67–69%) than that of U.S. PWRs (91.7%). This difference can be attributed to their respective supply–demand margins: a 4-pack MHTGR provides only a 40-MWe margin, whereas a typical PWR provides approximately 500 MWe. Consequently, a 4-pack MHTGR is more susceptible to output variability and more likely to experience demand shortfalls than a large PWR unit.

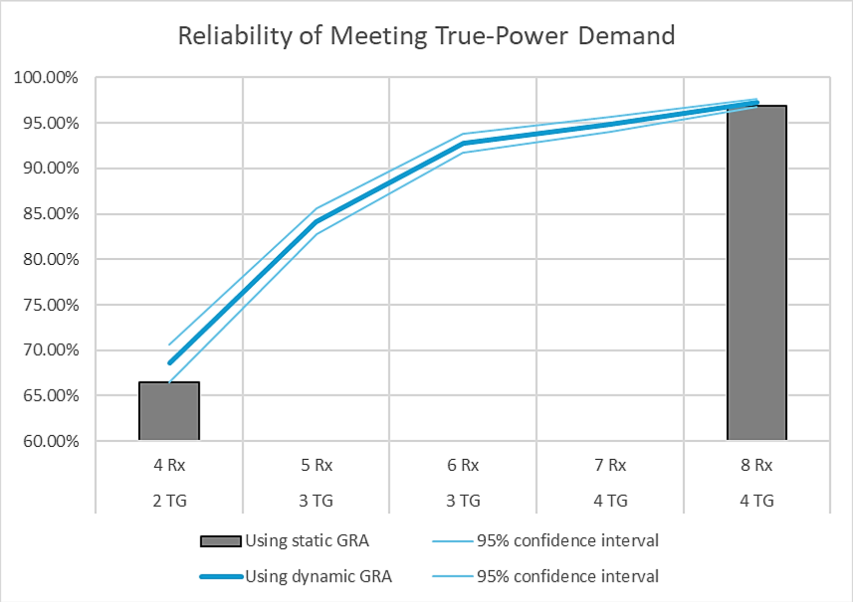


Figure 16. Grid electrical power needed to match MHTGR electricity supply reliability to its steam supply reliability.

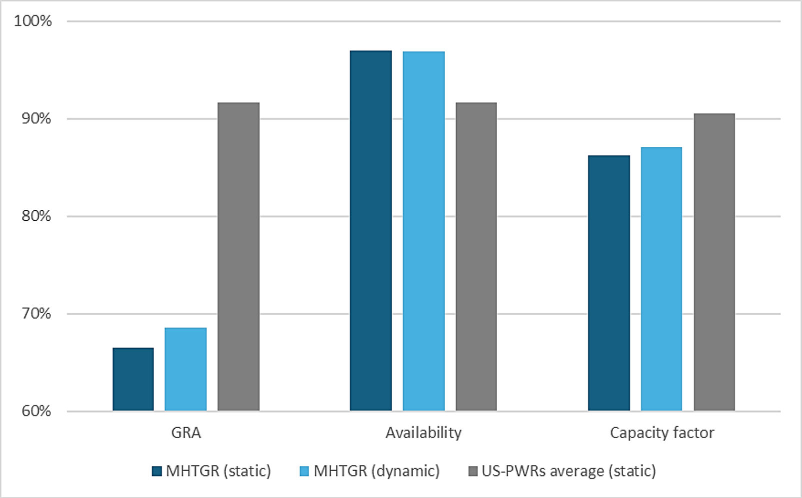


Figure 17. Grid electrical power needed to match MHTGR electricity supply reliability to its steam supply reliability.

Figure 16 and Figure 17 indicate strong agreement between the results generated by the static and dynamic GRA models. Minor discrepancies can be attributed to differences in model features and capabilities. In the dynamic GRA, loss of house load for a 4-pack MHTGR is modeled as an event involving the simultaneous loss of offsite power and both turbine generators; this event is not represented in the static GRA model. The dynamic GRA also incorporates common-cause events for random failures that lead to partial derates or complete shutdowns. In addition, it includes dynamic dependencies, such as logical derate progressions (Figure 4) and reactor coping-time characteristics (Figure 6). Conversely, the static GRA approach provides superior characterization of rare events through statistical cutset processing, a capability that is absent in the dynamic GRA framework.

4. CONCLUSION

This work applied static and dynamic Generation Risk Assessment (GRA) methods to evaluate how reliably a four-reactor, two-turbine MHTGR-based Integrated Energy System can meet the steam and electricity demands of a high-temperature electrolysis facility. The dynamic GRA captured time-dependent behaviors such as staggered startups, maintenance cycles, repair actions, coping-time dependencies, and derate progressions, providing insights beyond those available from static PRA.

Results show that the baseline configuration provides high steam-supply reliability but only moderate reliability in simultaneously meeting steam and electricity demand, driven primarily by limited redundancy and the sensitivity of electrical output to reactor or turbine outages. Increasing the number of reactor and turbine units significantly improves reliability and reduces uncertainty from random failures. Turbine-generator systems were identified as major contributors to derates, while startup effects remained minor.

Sensitivity studies demonstrated that generation reliability is largely unaffected by assumptions about cumulative versus non-cumulative turbine derates. Several complementary strategies—such as energy storage, peaking resources, or grid supplementation—can further improve reliability without solely relying on additional reactor capacity.

Overall, dynamic GRA offers valuable system-level insights into performance limitations, dominant contributors to unreliability, and tradeoffs among redundancy, derate logic, and supplemental power options. Future work should integrate techno-economic analysis to determine cost-optimal approaches for ensuring reliable, resilient operation of MHTGR-supported industrial processes.

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