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MULTICRITERION BENEFIT EVALUATION OF DEPLOYING NEW BATTERY TECHNOLOGY WITH INCREASED CAPACITY AT A GENERIC NUCLEAR POWER PLANT

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ABSTRACT

Nuclear power plant (NPP) safety improvements are routinely made by plant licensees and regulators. Examples of plant improvements include accident-tolerant fuel, diverse and flexible coping strategies, passive cooling systems, and increased battery capacity. A combined use of these plant improvements could lead to plant designs with enhanced resilience, allowing NPPs to better cope with both internal and external hazards and keep the plant operating safely, efficiently, and economically. This paper focuses on increased battery capacity and evaluates the potential costs and benefits of deploying batteries with increased capacities at a generic boiling water reactor (BWR) NPP. A multicriterion benefit evaluation methodology is used for the cost-benefit analysis. Ten alternatives for extending battery capacity are developed, including eight alternatives to provide additional direct-current power and one alternative to provide additional alternating-current power. Potential benefits of reducing plant risk are quantified through incorporating the alternatives into loss-of-offsite-power scenarios of the generic BWR probabilistic risk assessment model. Potential costs of implementing the alternatives are qualitatively discussed and ranked. The alternatives are then compared based on their impacts on plant risk and economics.

Key Words: Probabilistic risk assessment; Multicriterion benefit evaluation; Nuclear power plant; Increased battery capacity; Safety enhancement

1 INTRODUCTION

Safety enhancements for nuclear power plants (NPPs) are made routinely by plant licensees and regulators. They can also be responses that incorporate feedback from operational experience, such as post-Fukushima safety enhancements implemented at NPPs worldwide. Examples of plant improvements include accident-tolerant fuel, a diverse and flexible coping strategy (FLEX), a passive cooling system, and increased battery capacity. Combined use of these plant improvements has potential to lead to plant designs with enhanced resilience, which can better cope with both internal and external hazards and keep the plant operating safely, efficiently, and economically.

Idaho National Laboratory has developed a new methodology within the Enhanced Resilient Plant project under the Risk-Informed Systems Analysis Pathway of the United States (U.S.) Department of Energy's (DOE's) Light Water Reactor Sustainability (LWRS) Program to evaluate the impacts of safety enhancements on NPP safety and economics [1-4]. The proposed methodology is the multicriterion benefit evaluation (MCBE) methodology [5]. The MCBE methodology features (1) conducting holistic multicontext (plant normal operations, incidents, and accidents) and multicriterion (plant risk, plant revenue, and plant monetary cost) evaluation, (2) modeling dependencies among benefits through different types of influence paths (direct benefits through original and extended uses of safety enhancements, and indirect benefits achieved from risk-informed activities), and (3) converting calculated costs and benefits to perceived values based on a modified usage of cumulative prospect theory.

The MCBE methodology has been applied to evaluate the implementation of FLEX strategy at a generic pressurized water reactor (PWR) plant in fiscal year 2020 [5]. The efforts in the current fiscal year are focused on applying MCBE to evaluate the potential costs and benefits of deploying batteries with extended capacity at a generic boiling water reactor (BWR) plant. The battery study is ongoing, so this paper reports the analysis results to date. The evaluation of potential benefits in reducing plant risk through original uses of batteries is completed and summarized in this paper, although the benefits through extended uses and risk-informed activities are still under analysis. It should be noted that the battery study is an illustrative generic example, and its results do not represent benefits in any real-world plant. Section 2 develops a set of alternatives to extending battery capacity. Section 3 quantifies the potential benefits in reducing plant risk. Section 4 qualitatively discusses and ranks the potential costs. Section 5 compares all the alternatives based on their impacts on plant risk and cost. Section 6 concludes this paper.

2 DEVELOPING ALTERNATIVES FOR EXTENDING BATTERY CAPACITY

Nuclear industry has been actively seeking for solutions of expanding battery capacity by exploring new battery technologies with improved energy density (e.g., lithium-ion batteries) and developing new battery-powered systems supplying power more rapidly and more precisely [6]. This paper conducts an independent study for MCBE evaluation and develops alternatives for extending battery capacity at a generic BWR plant. Most safety-critical functions at NPPs are supported by alternating current (AC) and direct current (DC) electric power. Plant AC power is usually supplied from offsite; if loss-of-offsite-power (LOOP) occurs, AC power will be provided by onsite standby power sources, typically emergency diesel generators (EDGs). If LOOP occurs with concurrent standby AC power-source failures, there will be no AC power supply and the plant will enter a station blackout (SBO) situation. When AC power restoration is in progress, onsite batteries may continue to supply DC power with a limited capacity (e.g., 4 to 8 hours) and maintain safety-critical functions.

On one hand, extending battery capacity could provide additional DC power supply. In the generic BWR plant used for this case study, DC power supply is very critical for mitigating SBO. Many SBO mitigating systems (e.g., high pressure injection system and low pressure injection system) are dependent on DC power. Although many mitigating systems are designed to be capable of performing their safety functions when AC power supply is lost, they may need DC power for control and instrumentation purposes. In addition, the time to battery depletion sets time windows for offsite and onsite AC power recovery. On the other hand, extending battery capacity might supply additional AC power converted from the battery-generated DC power.

Nine alternatives of extending battery capacity are developed and presented in Table I. It should be noted that the list is not intended to be exhaustive since it is a conceptual and illustrative example. The list is subject to change after engaging industry partners to evaluate the feasibility of listed alternatives and potentially propose additional alternatives. The battery depletion time in the generic BWR plant is currently assumed to be 4 hours; on this basis, alternatives are developed to extend battery life to 8 hours, 12 hours, and 24 hours. Even with the same objective (e.g., extending battery life from 4 hours to 8 hours), a variety of alternatives can be formulated given different options in the battery portfolio (i.e., existing vs. new batteries), connection types (i.e., in series vs. in parallel), and so forth.

Table I. Alternatives of extending battery capacity at a generic BWR plant

No.	Alternative	Purpose
1	Extending battery life to 8 hours (extending life of existing batteries by load shedding)	Providing additional DC power
2	Extending battery life to 8 hours (keeping existing batteries and introducing new batteries)	Providing additional DC power
3	Extending battery life to 8 hours (replacing existing batteries with new batteries with extended life)	Providing additional DC power
4	Extending battery life to 12 hours (extending life of existing batteries by load shedding)	Providing additional DC power
5	Extending battery life to 12 hours (keeping existing batteries and introducing new batteries)	Providing additional DC power
6	Extending battery life to 12 hours (replacing existing batteries with new batteries with extended life)	Providing additional DC power
7	Extending battery life to 24 hours (keeping existing batteries and introducing new batteries)	Providing additional DC power
8	Extending battery life to 24 hours (replacing existing batteries with new batteries with extended life)	Providing additional DC power
9	Introducing new batteries as backup for onsite EDGs	Providing additional AC power

3 QUANTIFYING IMPACTS ON PLANT RISK

This section quantifies the impact on plant risk due to implementation of each alternative. The risk metric adopted in this paper is core damage frequency (CDF) estimated using probabilistic risk assessment (PRA). Although a variety of initiating events could lead to core damage (CD), this paper focuses on LOOP scenarios where DC power supply play a critical role.

This study features a generic PRA model developed using Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (SAPHIRE 8) at a generic BWR plant for LOOP scenario analysis. The generic BWR LOOP PRA model starts with the occurrence of a LOOP event. A LOOP event can be assigned to one of four categories, including grid-related (GR), plant-centered (PC), switchyard-centered (SC), and weather-related (WR). Four LOOP event trees are developed corresponding to four LOOP categories. All four LOOP event trees share the same tree structure but differ in initiating-event frequencies and AC power non-recovery probabilities. The four LOOP event trees are quantified with SAPHIRE 8. Table II presents the quantification results, which are used as the baseline risk estimates to compare and examine the risk impacts of battery capacity-extension alternatives.

Table II. LOOP event trees quantification results (baseline risk)

LOOP Category	No. of LOOP CD Sequences	No. of SBO CD Sequences	No. of Non-SBO CD Sequences	CDF (per reactor year)
LOOPGR	159	104	55	5.0E-07
LOOPPC	159	104	55	7.4E-08
LOOPSC	159	104	55	5.8E-07
LOOPWR	159	104	55	5.6E-07
Total	636	104	55	1.7E-06

3.1 Risk Impacts of Alternatives of Providing Additional DC power (Alternatives #1-8)

In the generic BWR LOOP PRA model, the impacts of batteries are reflected through two paths. One path is directly incorporating battery failure modes into the fault trees representing structure, system, and component (SSC) failures. As shown in Figure 1, an example is a fault tree for "diesel generator 1A support power faults." Two battery-related basic events are directly incorporated into the fault tree, including (1) DCP-BAT-LP-1A, (independent) failure of Train 1 125V DC battery, and (2) DCP-BAT-CF-125V, common-cause failure of two 125V DC batteries. However, the risk impact of a battery from such direct incorporation is negligible—the scenarios containing battery failures account for 2% of total LOOP CDF. It could be expected that the risk impact of battery capacity extension can be trivial as well. Hence, this path of direct incorporation will not be examined in further analysis.

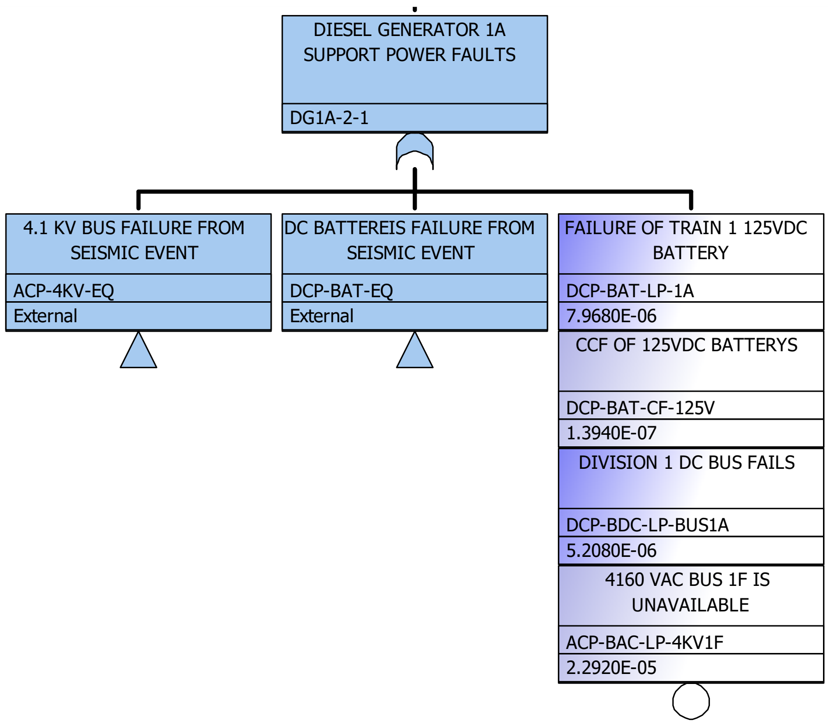

Figure 1. Example of direct incorporation of battery failures into PRA model.

The other path evaluating the risk impact of battery in the LOOP PRA model assesses the impacts of extended battery capacity on the human error probabilities (HEPs) of AC power recovery actions. Based on the U.S. NPP operating experience data, the non-recovery events of offsite power and onsite EDGs were found to be the best fit, with a lognormal distribution and a Weibull distribution, respectively [7]. The corresponding HEPs can be estimated using Equations (1) and (2) [7].

$$P_{OPR(t)} = \Phi[\frac{\ln(t)-\mu}{\sigma}] \tag{1}$$

$$P_{DGR(t)} = e^{-(\frac{t}{\beta})^{\alpha}} \tag{2}$$

Where t is AC power (from offsite source or onsite EDGs), recovery time is measured in hours, $P_{OPR(t)}$ is the probability of an operator failing to recover offsite power within t hours, $P_{DGR(t)}$ is the probability of an operator failing to recover EDG within t hours, μ and σ are lognormal distribution parameters, α and β

are Weibull distribution parameters. The lognormal and Weibull distribution parameter values used in this study were determined based on [7], which was the latest available version when the generic BWR SAPHIRE model was developed. It should be noted that usually these values are being updated annually. As of April 2021, the most recent versions are provided in [8] and [9]. Based on Equations (1) and (2), it is possible to estimate the non-recovery probabilities for offsite power and onsite EDGs given extended battery life shown in Table III. The LOOP CDF values given extended battery life are then quantified with SAPHIRE 8 and presented in Table IV. If the battery life can be extended from 4 hours to 8 hours, 12 hours, and 24 hours, the LOOP CDF is estimated to reduce by 6%, 11%, and 20%, respectively.

Table III. AC power recovery HEPs

t	P_(OPR(t))	P_(DGR(t))
4 hours (baseline)	3.1E-01 (GR); 1.1E-01 (PC); 2.1E-01 (SC); 5.5E-01 (WR)	7.3E-01
8 hours	1.4E-01 (GR); 4.7E-02 (PC); 1.0E-01 (SC); 4.1E-01 (WR)	6.0E-01
12 hours	7.4E-02 (GR); 2.6E-02 (PC); 6.2E-02 (SC); 3.4E-01 (WR)	5.1E-01
24 hours	2.1E-02 (GR); 8.1E-03 (PC); 2.3E-02 (SC); 2.1E-01 (WR)	3.3E-01

Table IV. LOOP CDF results (per reactor year) given extended battery life

LOOP Category	4 hours (baseline)	8 hours	12 hours	24 hours
LOOPGR	5.0E-07	4.7E-07	4.6E-07	4.3E-07
LOOPPC	7.4E-08	7.2E-08	7.1E-08	6.9E-08
LOOPSC	5.8E-07	5.6E-07	5.4E-07	5.1E-07
LOOPWR	5.6E-07	5.0E-07	4.6E-07	3.7E-07
Total	1.7E-06	1.6E-06	1.5E-06	1.4E-06
Delta	0.0E+00	-1.1E-07	-1.8E-07	-3.3E-07
Delta%	0%	-6%	-11%	-20%

The results shown in Table IV assume the battery (including switchyard batteries when needed) life is successfully extended. However, the alternatives of extending battery capacity are conditioned on battery reliability and different sets of human actions which need to be performed after LOOP occurs and are not always successful. When calculating the risk impacts of each battery capacity extension alternative, the results in Table IV need to be adjusted by considering the success probabilities of extension alternatives. If assuming the reliability of new batteries is on the same or better level than that of existing batteries, the battery failure probability is usually much lower than error probabilities of human actions, and thus are not further examined. The human actions determining alternative success probability are presented in Table V.

- For alternatives 1 and 4, operators need to perform load shedding to extend battery life. A recent U.S. Nuclear Regulatory Commission (NRC) study [10] on performing load shedding at a BWR was used as the basis to estimate the load-shedding HEPs for this paper. Although the NRC study was conducted for scenarios using FLEX strategy, it has an analogy to this study in both the BWR focus and the LOOP-mitigation context. The NRC study estimated that the HEP of performing FLEX DC load shedding for a BWR ranges from 2E-03 to 6E-03. This study adopts the minimum and average of this range as the HEPs for human action #1.1 and #4.1, respectively, considering that extending to a longer life requires shedding more loads, involves more manipulations, and increases the probability of human error.

- For alternatives 2, 5, and 7, existing batteries and new batteries were used in series to provide prolonged DC power supply. Before existing batteries deplete, operators need to start new batteries to continue power supply. This study assumes the level of complexity does not vary with the capacities of new batteries and adopts a generic value of 1.1E-02 as the same HEP for human actions #2.1, #5.1, and #7.1. Such value is obtained by adding up a diagnosis HEP of 1E-02 and an action HEP of 1E-03, which are the base rates used in the Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H) method [11].
- For alternatives 3, 6, and 8, existing batteries were replaced by new batteries with extended capacity. Such replacements should be completed during normal plant operations and maintenance, and no additional human actions need to be performed after LOOP. The corresponding HEPs are thus assumed as zero.

Table V. Post-LOOP human actions affecting alternatives of providing additional DC power

No.	Alternative	Influencing Human Action	HEP
1	Extending battery life to 8 hours (extending life of existing batteries by load shedding)	(#1.1) Operators perform load shedding	2E-03
2	Extending battery life to 8 hours (keeping existing batteries and introducing new batteries)	(#2.1) Operators start new batteries before existing batteries deplete	1.1E-02
3	Extending battery life to 8 hours (replacing existing batteries with new batteries with extended life)	None	0
4	Extending battery life to 12 hours (extending life of existing batteries by load shedding)	(#4.1) Operator perform load shedding	4E-03
5	Extending battery life to 12 hours (keeping existing batteries and introducing new batteries)	(#5.1) Operators start new batteries before existing batteries deplete	1.1E-02
6	Extending battery life to 12 hours (replacing existing batteries with new batteries with extended life)	None	0
7	Extending battery life to 24 hours (keeping existing batteries and introducing new batteries)	(#8.1) Operators start new batteries before existing batteries deplete	1.1E-02
8	Extending battery life to 24 hours (replacing existing batteries with new batteries with extended life)	None	0

By incorporating the effects of extended AC power-recovery time windows and potential human errors when extending the time windows in the PRA model, the projected risk-reduction impacts of alternatives #1–8 can be calculated and shown in Table VI. It can be observed that the effects on LOOP CDF reduction of multiplying (1-HEP) are negligible since the HEPs are quite low. But this does not suggest waiving the process of estimating and incorporating HEPs. The study in this paper is a generic, illustrative example, and the plant-specific, real-world analyses may yield significantly different HEP estimates.

Table VI. LOOP CDF-reduction impacts of alternatives for providing additional DC power

No.	Alternative	LOOP CDF Reduction (%)
1-3	Extending battery life to 8 hours	6%
4-6	Extending battery life to 12 hours	11%
7	Extending battery life to 24 hours (keeping existing batteries and introducing new batteries)	19%
8	Extending battery life to 24 hours (replacing existing batteries with new batteries with extended life)	20%

3.2 Risk Impact of Alternative of Providing Additional AC power (Alternative #9)

In the generic BWR LOOP scenarios, AC power can be supplied by one of three onsite EDGs (two regular and one supplementary). To evaluate the risk impact of alternative 9, a system consisting of battery and inverter (converting DC power to AC power) is incorporated into the fault trees as the fourth onsite AC supply source. SSC failure modes of this alternative include battery failure and inverter failure, but their failure probabilities are usually much lower than error probabilities of human actions. This alternative involves one human action of aligning the battery and inverter. The HEP of this action is estimated as 1.1E-02 in a similar way of estimating HEPs for actions #2.1, #5.1 and #7.1. The projected risk-reduction impact of alternative 10 is quantified with SAPHIRE 8 and presented in Table VII.

Table VII. LOOP CDF-reduction impact of alternative of providing additional AC power

No.	Alternative	LOOP CDF Reduction (%)
9	Introducing new batteries as backup for onsite EDGs	41%

4 EVALUATING IMPACTS ON PLANT ECONOMICS

This section qualitatively discusses the projected costs of implementing the alternatives of extending battery capacity at the generic BWR plant. The projected costs are additional costs compared to the current base case of utilizing batteries with 4-hour life. As shown in Table VIII, all the alternatives are projected to incur the cost of updating procedures and conducting associated trainings to accommodate the mitigation-strategy changes. Alternatives 2, 5, 7, and 9 are projected to incur additional maintenance costs since existing batteries are kept and new batteries are introduced. With the exception of alternatives 1 and 4, all alternatives are projected to incur costs of purchasing and installing new batteries and/or inverters, and the costs are projected to vary with battery capacity. Assuming the batteries ordered for alternative 9 have a larger capacity than the batteries ordered for alternative 9 and further assuming the costs of purchasing batteries are much higher than maintenance costs, the projected costs of all the alternatives can be ranked as: C9 > C8 > C7 > C6 > C5 > C3 > C2 > C1 = C4. The projected costs of the alternatives can also be preliminarily categorized as three levels, including High Cost (alternative 9), Medium Cost (alternatives 2, 3, 5, 6, 7, and 8), and Low Cost (alternatives 1 and 4).

Table VIII. Projected costs for alternatives of extending battery capacity at a generic BWR plant

No.	Alternative	Projected Costs
1	Extending battery life to 8 hours (extending life of existing batteries by load shedding)	Cost of updating procedures and training
2	Extending battery life to 8 hours (keeping existing batteries and introducing new batteries)	Cost of purchasing and installing new batteries with 4-hour life; cost of updating procedures and training; maintenance cost for new batteries
3	Extending battery life to 8 hours (replacing existing batteries with new batteries with extended life)	Cost of purchasing and installing new batteries with 8-hour life; cost of updating procedures and training
4	Extending battery life to 12 hours (extending life of existing batteries by load shedding)	Cost of updating procedures and conducting training
5	Extending battery life to 12 hours (keeping existing batteries and introducing new batteries)	Cost of purchasing and installing new batteries with 8-hour life; cost of updating procedures and training; maintenance cost for new batteries
6	Extending battery life to 12 hours (replacing existing batteries with new batteries with extended life)	Cost of purchasing and installing new batteries with 12-hour life; cost of updating procedures and training
7	Extending battery life to 24 hours (keeping existing batteries and introducing new batteries)	Cost of purchasing and installing new batteries with 20-hour life; cost of updating procedures and training; maintenance cost for new batteries
8	Extending battery life to 24 hours (replacing existing batteries with new batteries with extended life)	Cost of purchasing and installing new batteries with 24-hour life; cost of updating procedures and training
9	Introducing new batteries as backup for onsite EDGs	Cost of purchasing and installing inverters and new batteries with capacities comparable to EDGs; cost of updating procedures and training; maintenance cost for new batteries

5 CONDUCTING ALTERNATIVE COMPARISON

This section compares the alternatives of extending battery capacity from the perspectives of plant risk and plant economics. The risk impacts (quantified in Section 3) and the cost impacts (qualitatively ranked in Section 4) of all the alternatives are displayed in Figure 2.

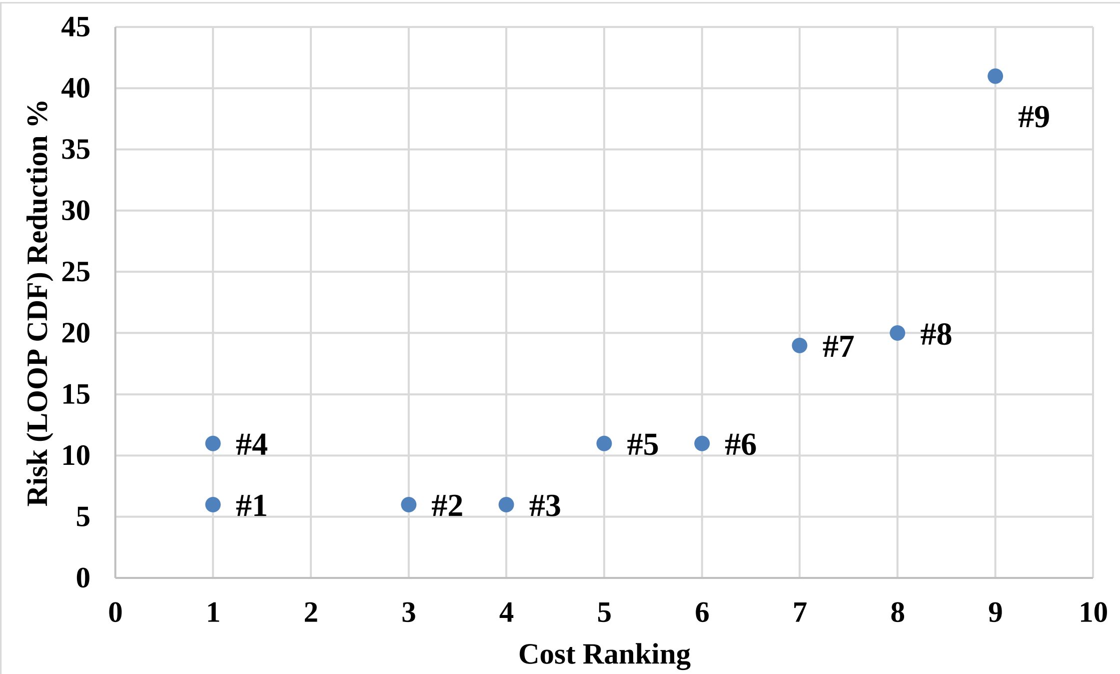

Figure 2. Impacts on plant risk and cost of implementing alternatives of extending battery capacity at a generic BWR plant. Risk impact is quantitatively measured using percentage of LOOP CDF reduction in y-axis. Cost impact is not quantified but qualitatively ranked in x-axis (1 as lowest cost and 10 as highest cost).

It can be observed that alternative 9 is estimated to have the largest risk reduction but with the largest projected cost. Alternatives 1 and 4 are projected to have the same lowest cost but alternative 4 is estimated to have a larger risk reduction. Based on this figure, the impacts on plant risk and economics appear to be competing against each other. It is worthwhile to mention that this competing relationship is obtained from the limited analysis scope in this paper which only considers the accident-mitigation benefits of batteries. If the benefits of supporting normal operation and maintenance can be evaluated in future research, the relationship between plant risk and cost impacts may be different.

6 CONCLUSIONS

This paper evaluates the potential costs and benefits of deploying batteries with increased capacities at a generic BWR plant using the MCBE methodology. Nine alternatives for extending battery capacity are developed, including nine alternatives for providing additional DC power and one alternative for providing additional AC power. Potential benefits of reducing plant risk are quantified through incorporating the alternatives into LOOP scenarios of the generic BWR PRA model. Potential costs of implementing the alternatives are qualitatively discussed and ranked. The alternatives are compared based on their impacts on plant risk and economics. The current list of alternatives will be presented to industry partners to evaluate the feasibility of listed alternatives and potentially propose additional alternatives.

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8 REFERENCES

1. Z. Ma, C. Parisi, H. Zhang, D. Mandelli, C. Blakely, J. Yu, B. Youngblood, & N. Anderson, "Plant-Level Scenario-Based Risk Analysis for Enhanced Resilient PWR – SBO and LBLOCA," INL/EXT-18-51436, Idaho National Laboratory, https://doi.org/10.2172/1495192 (2018).
2. Z. Ma, C. Parisi, C. Davis, J. Park, R. Boring, & H. Zhang, "Risk-Informed Analysis for an Enhanced Resilient PWR with ATF, FLEX, and Passive Cooling," INL/EXT-19-53556, Idaho National Laboratory, https://doi.org/10.2172/1777257 (2019).
3. Z. Ma, C. Davis, C. Parisi, R. Dailey, J. Wang, S. Zhang, H. Zhang, & M. Corradini, "Evaluation of the Benefits of ATF, FLEX, and Passive Cooling System for an Enhanced Resilient PWR Model," INL/EXT-19-56215, Idaho National Laboratory, https://doi.org/10.2172/1777262 (2019).
4. Z. Ma, S. Zhang, H. Zhang, J. Park, J. Yu, C. Blakely, T. Ulrich, & R. Boring, "Risk-Informed ATF and FLEX Analysis for an Enhanced Resilient BWR under Design-Basis and Beyond-Design-Basis Accidents," INL/EXT-20-59906, Idaho National Laboratory, https://doi.org/10.2172/1777266 (2020).
5. S. Zhang, Z. Ma, H. Zhang, and C.L. Smith, "Multicriterion Benefit Evaluation Methodology for Safety Enhancements in Nuclear Power Plants and Application for FLEX Strategies," *Nuclear Engineering and Design*, **Volume 376**, https://doi.org/10.1016/j.nucengdes.2021.111135 (2021).
6. Nuclear Energy Institute, "Delivering the Nuclear Promise 2020 Top Innovative Practice: Exelon – BlackStarTech™", https://www.nei.org/CorporateSite/media/filefolder/resources/delivering-nuclear-promise/2020/DNP-TIP-2020-10-TIP-Entry-Exelon-BlackStarTech.pdf (2020).
7. N. E. Johnson and J.A. Schroeder, "Analysis of Loss-of-Offsite-Power Events 1997–2015," INL/EXT-16-39575, Idaho National Laboratory, https://doi.org/10.2172/1369381 (2016).
8. N. Johnson and Z. Ma, "Analysis of Loss-of-Offsite-Power Events: 1987–2018," INL/EXT-19-54699, Idaho National Laboratory, https://doi.org/10.2172/1755379 (2019).
9. Z. Ma, "Enhanced Component Performance Study: Emergency Diesel Generators 1998–2018," INL/EXT-19-54609, Idaho National Laboratory, https://doi.org/10.2172/1631738 (2019).
10. S. Cooper and C. Franklin, "FLEX HRA using IDHEAS-ECA," Presentation at the Advisory Committee on Reactor Safeguards Probabilistic Risk Assessment Subcommittee Meeting, United States Nuclear Regulatory Commission, https://www.nrc.gov/docs/ML2026/ML20267A194.pdf (2020).
11. D. Gertman, H. Blackman, J. Marble, J. Byers, and C. Smith, "The SPAR-H Human Reliability Analysis Method," NUREG/CR-6883, United States Nuclear Regulatory Commission, https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6883/cr6883.pdf (2005).