Molten Salt vs. Liquid Sodium Receiver Selection Using the Analytic Hierarchy Process

Preprint

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Molten Salt vs. Liquid Sodium Receiver Selection Using the Analytic Hierarchy Process

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Abstract. An international team led by NREL analyzed the favorability of two alternative liquid receiver designs for a 700+ °C receiver under the Gen3 CSP Liquid Pathway project. The competing liquid heat transfer fluids were a ternary chloride salt and liquid-metal sodium. The team applied a facilitated analytic hierarchy process (AHP) to arrive at a recommended alternative and set a path forward for the project. The AHP criteria were formulated, weighted, and scored by the project leadership team and technical advisory committee consisting of energy industry and CSP experts. The six-month process culminated with a two-day workshop where the sodium alternative was deemed to have both a significantly higher benefit (19.3%) and a lower LCOE (11.4%), with only a slightly higher risk (~3%) than the salt alternative. Consequently, a sodium-receiver design was selected for the Liquid Pathway project, where it will be used to charge a two-tank chloride salt thermal energy storage system.

NOMENCLATURE

AHP	Analytic Hierarchy Process
ANU	Australian National University
ASTRI	Australian Solar Thermal Research Institute
CSP	Concentrating solar power
DOE	United States Department of Energy
HTF	Heat transfer fluid
LCOE	Levelized cost of energy
NREL	National Renewable Energy Laboratory
RD&D	Research, development and deployment
SAM	System Advisor Model
sCO_2	Supercritical carbon dioxide
TES	Thermal energy storage
USD	U.S. dollars

INTRODUCTION

Next-generation central receiver systems are targeting operating temperatures above 700°C and use of a closed Brayton supercritical CO_2 power cycle in an effort to achieve higher efficiencies and lower levelized cost of electricity (LCOE). As part of the Generation 3 Concentrating Solar Power Systems Program (Gen3 CSP), the U.S. Department of Energy is funding the National Renewable Energy Laboratory (NREL) to design, develop, test, and validate a 1-MWt liquid heat-transfer system consisting of a solar receiver, thermal energy storage unit, primary heat exchanger, and associated pumps, piping, valves, sensors, and heat tracing. In Phase 1 of the project, two high-temperature solar receivers, capable of operation at 720°C or higher, were designed: NREL led development of a molten-salt receiver based on the use of $MgCl_2$-KCl-NaCl salt, and the Australian National University (ANU) led a team that developed a liquid sodium (100% Na) receiver. The Australian work is funded by the Australian Solar Thermal Research Institute (ASTRI) as part of a collaboration with the NREL team. It was necessary to down select a single receiver technology for further development in Phases 2 and 3, and the analytic hierarchy process (AHP) was used to evaluate the two technologies and support the selection decision.

The decision-making process leveraged experience from an Electric Power Research Institute (EPRI) Decision Framework that was developed to support planning and decision making for advanced nuclear technology [1]. The framework is grounded in scientifically defensible decision-making theory [2], [3], which can be utilized in a reproducible manner to facilitate evaluation of attributes for Gen3 CSP receivers. Such multi-criteria decision making (MCDM) tools have been used frequently for energy decision-making applications, where multiple criteria interact in a complex manner [4], [5].

Analytic Hierarchy Process

The analytic hierarchy process was selected for use in the NREL project based on past review of evaluation methods [6]. Thomas Saaty, who developed the AHP concept in 1990, taught that sound decisions can be made when we know “the problem, the need and purpose of the decision, their subcriteria, stakeholders and groups affected, and the alternative actions to take” [7]. The process was developed to help work through complicated, real-world prioritization scenarios. AHP is now considered to be the world’s leading multi-criteria decision-making methodology, per Gartner Inc. Today, AHP is widely used in the military, government, private sector, and academia to determine priorities and establish weighting factors.

AHP is based on mathematics and psychology. It simplifies the process of weighting the decision criteria by comparing two criteria at a time (i.e., pairwise comparisons) to determine which is more important with respect to the decision goal—and by how much. The AHP approach encourages decisions based on knowledge that supports the decision-making process, rather than intuition.

AHP employs a multi-level, hierarchical structure centered around an objective, attributes or criteria (potentially with layers of sub-criteria), and alternatives. For each criterion, the options are compared to one another in a series of pairwise comparisons. This framework allows for systematic weighting of the criteria to determine the prioritization of the inputs [8]. With accurately weighted decision criteria in-place, the feasible alternatives can then be evaluated and scored against each criterion. The result is a ranked order list of alternatives that summarizes the participants’ knowledge and wisdom. In the subject project, the objective was to select a preferred receiver technology for further development under the U.S. Department of Energy (DOE) Gen3 CSP Program. The alternatives were distinguished by the heat transfer fluid (HTF) used in the solar receiver: (i) a ternary chloride salt or (ii) liquid-metal sodium.

AHP has been applied to a number of case studies pertaining to electricity production. For example, in India AHP was used to analyze barriers to solar energy deployment [9]; AHP was used in China to assess a range of solar technologies, including CSP, PV, solar heating, solar cooling, and solar fuels; and the Republic of Korea has employed AHP on a number of occasions to inform its nuclear energy policies [10] and to allocate nuclear RD&D funding [11]. While the NREL project intended to use AHP strictly to down select a single receiver technology for further RD&D, the AHP also provides the ability to compare relative benefits and risks of alternatives instead of simply identifying a single top-performing option [12].

Several off-the-shelf, commercially available decision software tools that implement AHP are available (e.g., Expert Choice, Definitive Solutions, Transparent Choice, Decision Lens). While it is possible to conduct the decision process using a simple spreadsheet or free online software, an expert facilitator was preferred to ensure that the evaluation was conducted consistently and accurately, using a sound approach that leverages industry best practices. There is an art to selecting and weighting criteria, scoring the two alternatives, and moving participants toward consensus. The facilitator was responsible for making recommendations to the group based on the analysis, assessing alignment among individual participants, and examining sensitivities to the inputs.

APPROACH

Build the Decision Model

Participants in the process included four members from the project Leadership Team and eight technical advisory committee (TAC) members, representing expertise in power project development, owner's engineering, power cycle development, CSP technology, and utilities. The team first identified and prioritized the benefit and risk criteria that were used to build the decision models. The methodology depicted in FIGURE 1 leverages several key concepts and techniques:

- Treat ***cost as an independent variable***
- Create ***two decision models*** (Benefit and Risk)
- State decision criteria as ***objectives***
- Focus on decision criteria that are ***differentiators***
- Achieve the decision goal through cost, benefit, and risk ***trade-offs***

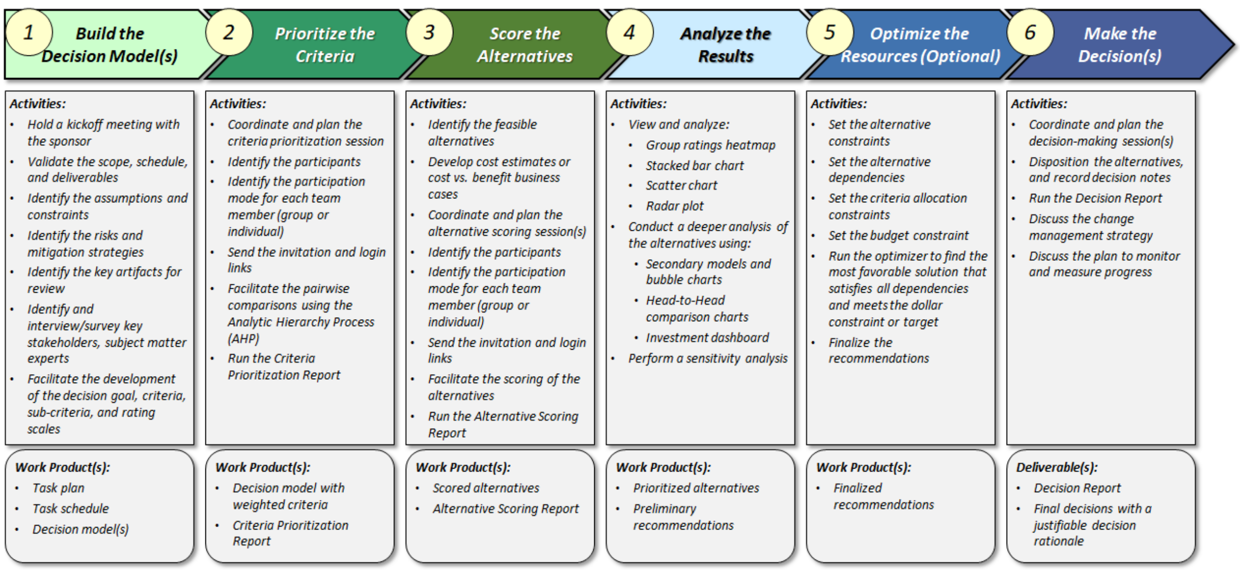

FIGURE 1. AHP decision making methodology.

The primary benefit of using these concepts and techniques is that it allows the decision team to more effectively measure and compare the incremental benefit, cost, and risk of the alternatives. The TAC and Leadership Team (100% participation) contributed 122 decision criteria ideas. The objective of this step was to collect and analyze the input received from team members, and to prepare a decision criteria feedback survey to determine which of the potential benefit and risk criteria were differentiators. The facilitator reviewed the criteria suggestions and comments to produce a rationalized and normalized list of potential benefit and risk criteria. The steps included:

1. Clarify the meaning of each criterion, as some contributors used terms that have multiple industry meanings or that result in vagueness to those who are not as familiar with the term
2. Note suggestions that are unclear and require additional information from the submitter
3. Note criterion that had two or more suggestions rolled into it, and categorize each to support survey development
4. Note whether one criterion is a duplicate of another. (Note: In those cases, the criteria were moved under a common parent, while keeping traceability)
5. Organize criteria and related subcriteria into hierarchies

Next the team reviewed the potential benefit and risk criteria to determine which were differentiators. Criterion deemed not to be differentiators were removed from further consideration as they would have no impact on the decision. Including only the differentiators ensures that the evaluation of the technology alternatives is more focused, and that the evaluation is centered on the key considerations.

Prioritize the Criteria

Prioritization was performed by making pair-wise comparisons between criteria.

1. First, a series of comparisons were performed to determine which of a set of criteria was more important with regard to achieving the objective. This was done for each possible pair of criteria to populate a comparison matrix. The matrix eigenvector was calculated to determine the relative criteria weightings.
2. Second, a similar process was conducted for the subcriteria under each criterion. This established a second level of detail to the weighting scheme. This step was repeated for each criterion in the two hierarchies.
3. Finally, an "inconsistency ratio" was calculated from the matrix eigenvalue. This ratio identified inputs from individual participants that were illogical based on existing inputs.

The resulting Benefit and Risk matrices are shown in FIGURE 2 and FIGURE 3.

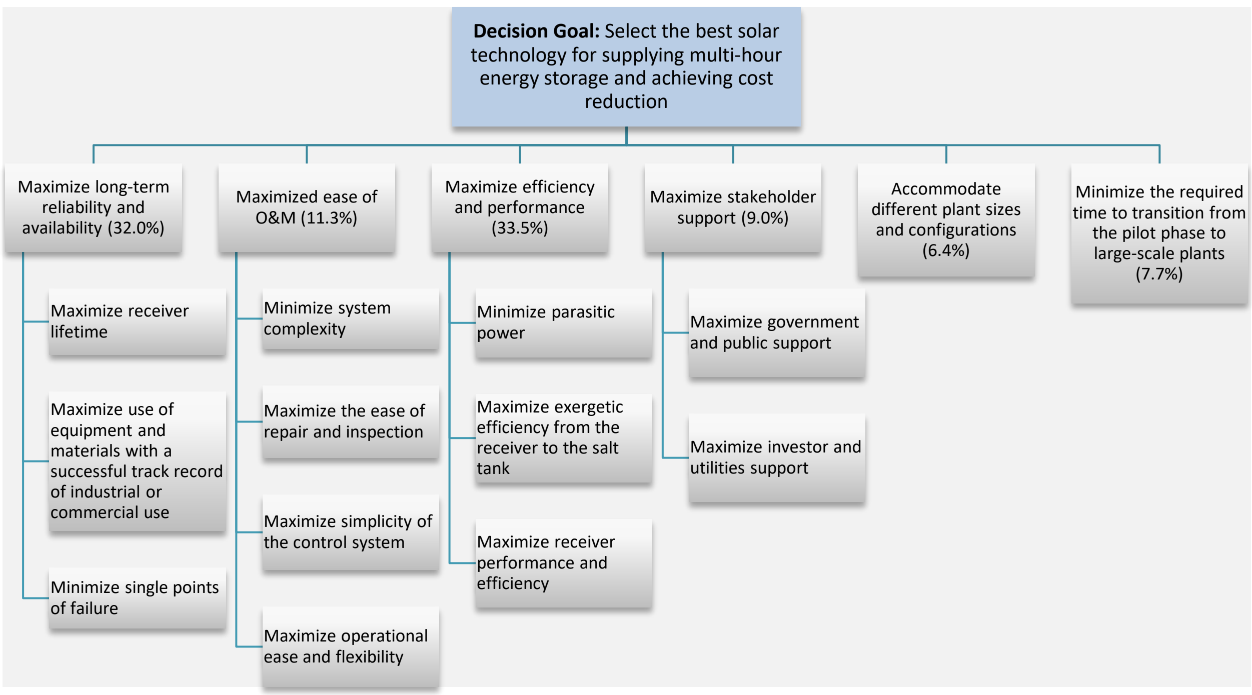

FIGURE 2. Benefit hierarchy with relative weighting designated by the percentages.

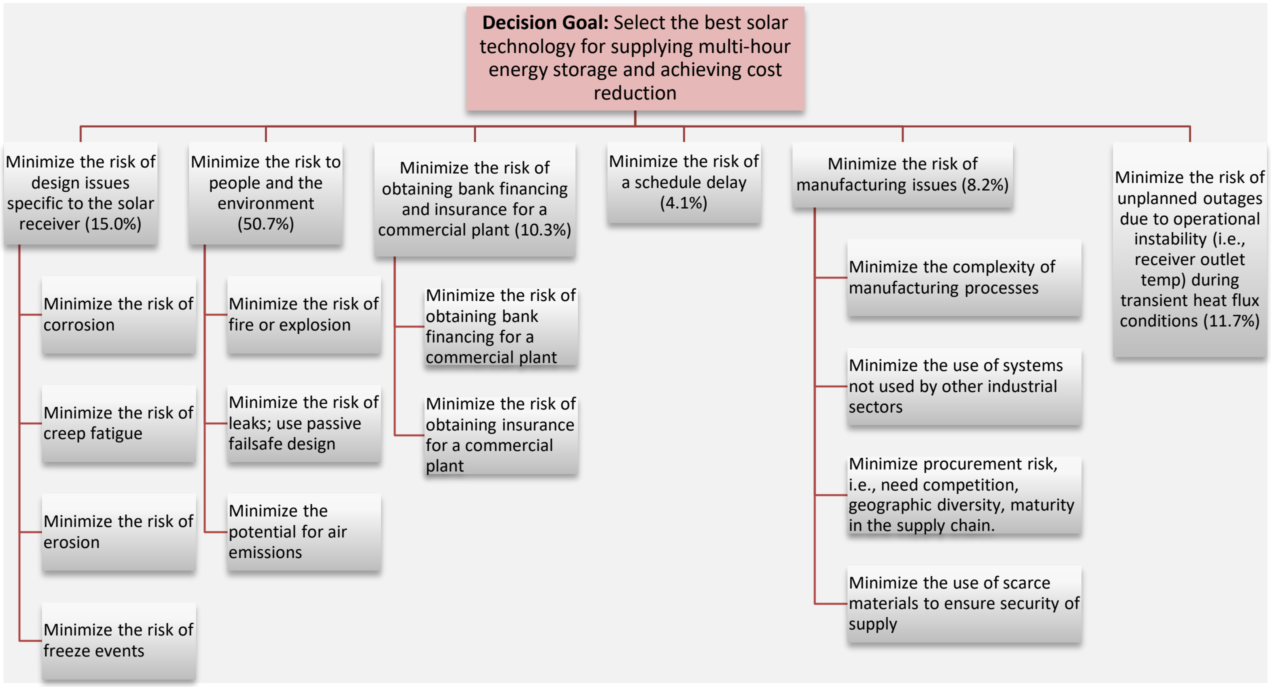

FIGURE 3. Risk hierarchy with relative weighting designated by the percentages.

Score the Alternatives

A 7-point scale was used for rating the decision criteria and subcriteria in the benefit and risk hierarchies. Each rating has weights and definitions associated with it. The definitions are either qualitative or quantitative, depending on whether reliable data exist for the two alternatives (chloride salt or sodium) for that particular criterion. For example, the rating scale for the benefit criterion "**Maximize receiver performance and efficiency**" is quantitative because of the availability of performance estimates for the two designs.

In February 2020, the team convened for a two-day meeting with the following objectives: (i) review and compare commercial-scale design and cost of the salt-receiver and sodium-receiver based CSP concepts, (ii) complete an AHP to compare the two design choices, and (iii) reach consensus within the Leadership Team on the selection and plan for moving forward with the selected receiver design.

In the weeks leading up to this meeting, three advisors from the TAC were unable to participate for various reasons. An additional reviewer/scorer with extensive CSP industry experience was identified and able to help fill the gap. The U.S. DOE representative on the Leadership Team deferred from the scoring, leaving a total of nine Leadership Team and TAC representatives participating in the scoring process.

On the first day of the meeting the project team gave overview presentations of the two alternatives. These included an engineering assessment of the performance of a commercial-scale version of each receiver, using a consistent set of design criteria and performance definitions as given in TABLE 1. The receiver efficiency was a quantitative metric based on estimates of efficiency by the ANU-led (sodium receiver) and NREL-led (salt receiver) teams. Leading up to the meeting, the teams had worked collaboratively to define the boundary conditions and then independently developed the two designs.

RESULTS

The AHP was facilitated by an impartial expert in AHP methods. Each participant was given two unique login links to the AHP software tool for the benefit and risk hierarchy scoring, respectively. Participants used laptops or mobile devices to enter scores. The facilitator guided the scoring process, allowing all participants to progress at the same rate and answer questions at the same time. A script was used for consistency in question presentation. Scores from all AHP participants were weighted equally.

Participants were encouraged to rely on the workshop presentations and their own expert judgment to score how well the two receiver alternatives met each of the criteria and subcriteria. Depending on the nature of the criteria, it was often helpful to intersperse presentation materials and discussions in between questions if participants had questions. Aggregate scores were displayed following each judgment to gauge consensus. The team frequently discussed the rationale for their responses, particularly when there was less consensus. Participants were given an opportunity to revise their scores based on new information or perspectives offered by other teammates.

TABLE 1. Commercial-scale receiver specifications for salt- and sodium-receiver alternatives.

Item	Reference design conditions or definition
Receiver design	Multiple flat panel, surround field
Receiver capacity	Approximately 500-600 MWt
Receiver outlet temperature	Salt: 720°C Sodium: 740°C (to account for 20 K drop across sodium-to-salt storage HX)
Receiver inlet temperature	Salt: 500°C Sodium: 520°C
Receiver ΔP	Salt: Constrained to ≤ 2.5 MPa Sodium: Estimated at approximately 100 kPa
Maximum salt or sodium velocity	Salt: ≤ 4.5 m/s Sodium: ≤ 2.4 m/s
Receiver tube coating	Default coating (Pyromark): 94% diffuse solar absorptivity / 89% emissivity High-performance coating: 98% diffuse solar absorptivity / 91% emissivity
Peak flux or lifetime methodology and constraints	Design lifetime estimated using inelastic FEA analysis based on methods from INL/ANL project "Creep-fatigue Behavior and Damage Accumulation of a Candidate Structural Material for Concentrating Solar Thermal Receiver" Estimated lifetime ≥ 30 years assuming an average of 10 hours of operation per day, 365 days per year
Mirror reflectivity	90%
Reflected image error	≥ 3mrad
Tower height and field layout	Selected independently for each configuration
Heliostat design	Selected independently for each configuration
Location	Daggett, CA
Sun shape	Limb-darkened sun
Atmospheric attenuation model	DELSOL3 clear day
Sun position	Daily simulations at hourly resolution on summer solstice, equinox, and winter solstice
DNI	Clear-sky profile with DNI = 950, 980, 930 W/m^2 at solar noon on the summer solstice, equinox, and winter solstice, respectively
Ambient Temp.	25°C
Wind speed	Case 1: 0 m/s; Case 2: 5 m/s at 10m
Wind speed scaling	$U(z) = U_{z=10\mathrm{m}} \left(\frac{z}{10}\right)^{\alpha}$ with $\alpha = 0.14$
Convective heat loss coefficient	Salt (external receiver): Siebers and Kraabel correlation (SAND84-8717) Sodium (cavity receiver): Clausing (https://doi.org/10.1115/1.3248095)
Tube material	Inconel 740H
Min. allowable tube wall	1.2 mm
TMY file for annual performance	daggett_ca_34.865371_-116.783023_psmv3_60_tmy.csv from NREL NSRBD
Method for extrapolating annual performance	Based on full-day simulations of the summer-solstice, equinox, and winter-solstice using clear-sky DNI, fixed ambient temperature, and fixed wind speed. NREL will provide comparisons between this estimate and System Advisor Model (SAM) annual-average performance for the salt receiver.

During the alternative scoring process, the salt receiver and sodium receiver technology alternatives were scored based on the rating scale definitions for each sub-criterion or criterion within each hierarchy and the judgment of each team member. There were two sub-criteria that were *not* scored qualitatively by the team: (i) Maximize exergetic efficiency from the receiver to the salt tank, and (ii) Maximize receiver performance / efficiency.

The exergy metric was calculated by ANU. The values used for the criteria represent exergy destruction in the receiver and heat exchanger (sodium technology only). Exergetic losses in the thermal energy storage system were not considered as this system was common to both receiver choices. The values were calculated from ANU's ASCEND design-point model results for total exergy loss (incident radiation exergy on receiver through power block). Exergy loss in the power block was subtracted from the total, resulting in exergy loss values of 38.5% for salt and 42.9% for sodium. The estimated exergy destruction in the heat exchanger was significantly lower than the radiative and convective losses, and consequently there was not a considerable difference in scores for the two alternatives. A range of 35% to 45% was selected for the criteria. It was noted that the current heat exchanger design is not optimized, and the exergy estimates were developed using property data for an earlier chloride salt. With a weighting of 6.1%, small changes in the scores for this subcriterion are unlikely to have a strong influence on the overall scores.

Similarly, receiver efficiency was scored based on quantitative estimates of efficiency. As noted, the two teams defined a common set of receiver performance specifications and efficiency was quantified by estimating the annual solar-to-thermal efficiency for the different designs. Based on a single-tower system design, the estimated annual solar-to-thermal efficiency was 42.4% for the sodium receiver and 37.2% for the salt receiver.

In summary, the team made a total of 216 judgments associated with the benefit hierarchy, and 270 judgments associated with the risk hierarchy, for a total of 486 judgments. The composite scores calculated by the software tool represent how well each receiver technology meets the criteria and subcriteria, adjusted by the relative weights of the criteria. The resulting scores for the two alternatives are an indication of how well the alternatives meet the overall objective set at the beginning of the AHP.

For the benefit hierarchy, a higher score represents a higher benefit. The sodium alternative had a 19.3% favorable benefit score when compared to the salt alternative. At the criteria level, the sodium alternative received a total benefit score of 66.1%, which equates to a group ranking of "Medium." The salt alternative received a total benefit score of 46.8%, which equates to a rating of "Medium-Low." These percentages are based on a hypothetical ideal alternative that could receive a total benefit score of 100% if it were to receive a "High" rating on every benefit criterion and sub-criterion. The relative strength of the sodium alternative can be seen by comparing the length of the weighted bars in FIGURE 4.

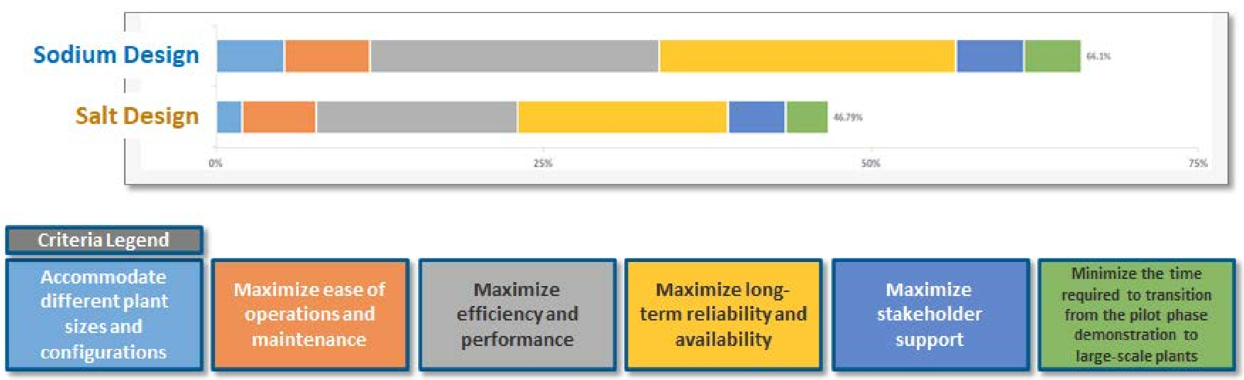

FIGURE 4. Benefit scoring results. Stacked bar chart (larger bar = higher benefit). The sodium receiver outscored salt on all benefit criteria.

For the risk hierarchy, a higher score represents a higher risk. At the criteria level, the salt alternative received a total risk score of 53.0%, while the sodium alternative received a total risk score of 56.1%. These percentages are based on a hypothetical ideal alternative that could receive a total risk score of 0% if it were to receive a "Does not contribute" rating on every risk criterion and sub-criterion. The relative strength of the salt alternative can be seen by comparing the length of the weighted bars in FIGURE 5. Sodium scored a lower risk in every criterion except the highly weighted "Minimize risk to people and environment." This highlights the historic challenge of sodium for heat transfer applications—great thermophysical properties and low corrosivity, but high fire danger if released to air.

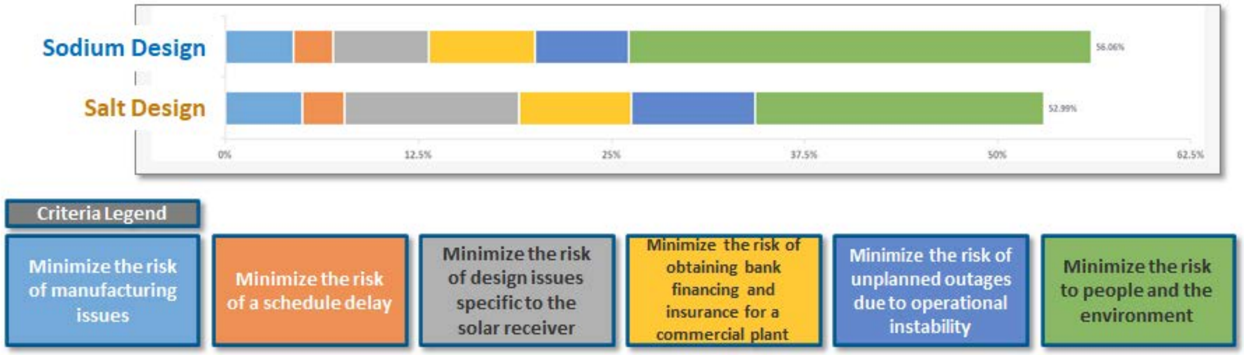

FIGURE 5. Risk scoring results. Stacked bar chart (larger bar = higher risk).

Lastly, the levelized cost of electricity (LCOE) was compared with the benefit and risk scores for the salt and sodium alternatives, as depicted in TABLE 2. ***The sodium alternative has both a significantly higher benefit (19.3%) and a lower LCOE ($9/MWh), with only a slightly higher risk (~3%) than the salt alternative.***

TABLE 2. The two alternatives scored closely in overall risk, with the sodium receiver showing advantages in benefit and cost metrics.

Metric	Alternative 001 Salt Receiver	Alternative 002 Sodium Receiver
Benefit Score (higher score is better)	46.8%	66.1%
Risk Score (lower score is better)	53.0%	56.0%
Cost (LCOE)	$79/MWh	$70/MWh

A key measure used to determine the quality of the AHP pairwise comparisons process is the inconsistency ratio (IR), which is calculated by dividing a consistency index (CI) by a random index (RI). An example of an inconsistent set of judgments in the context of pairwise comparisons is as follows: criterion "A" is more important than criterion "B"; criterion "B" is more important than criterion "C"; but then criterion "C" is more important than criterion "A." The IR for the benefit and risk hierarchy pairwise comparisons were 3.4% and 2.3%, respectively, which is extremely low. This indicates that the judgments provided by the team members during the pairwise comparisons associated with both hierarchies were very consistent. This can usually be attributed to having well-understood criteria with clear definitions.

CONCLUSION

The objective of the down selection meeting was to arrive at a recommended alternative and set a path forward for the project. The AHP results were reviewed by the Leadership Team, DOE, and EPRI after the scoring session. When the full team reconvened the following morning, participants were offered an opportunity to revise any scores from the previous day, before seeing any results. No one felt it necessary to make any revisions. The results were then presented to the team, and upon further discussion, there was unanimous consent from within the team to recommend the sodium alternative. The sodium alternative was deemed to have both a significantly higher benefit (19.3%) and a lower LCOE (11.4%), with only a slightly higher risk (~3%) than the salt alternative.

Key observations included the following:

- While the score for "Minimize risk to people and the environment" (FIGURE 5) was the primary factor that resulted in a higher risk for sodium, it did not seem to impact the scores for "Minimize the risk of obtaining bank financing and insurance for a commercial plant," which received roughly the same score for both receiver types. The group concluded that even with the perceived risk of sodium fires, it would be feasible to educate bank engineers and the public about sodium as a safe technology. There was a suggestion to focus in future project phases on reducing the risk of handling sodium and understanding safety measures. In the long-term, a public education campaign may be advisable. It was also noted that the scores for "Minimize risk to people and the environment" had very high consensus.

- In the benefit hierarchy, the sodium alternative scored higher than the salt alternative across all six criteria. The three biggest differentials between the salt and sodium criteria scores were (i) accommodate different plant sizes and configurations, (ii) maximize efficiency and performance, and (iii) maximize long-term reliability and availability. It was noted that the latter two criteria represent the ability for a plant to make money. This observation seemed to further solidify that the sodium receiver was the preferred technology.
- One of the criteria addressed the ability to "Accommodate different plant sizes and configurations," but the weighting for that criteria was only 6.4%. While the benefits of modularity may have been reflected in responses for other criteria, such as "Maximize ease of operations and maintenance" and "Maximize long-term reliability and availability," the differences between the sodium and salt scores for those criteria were not great enough to sway the overall benefit score.

During the follow-up session, the full team also reviewed a number of key measures, such as the inconsistency ratios and consensus ratings associated with the pairwise comparisons, and the consensus ratings associated with alternative scoring. The following question was posed: "Is there too much consensus?" This question arose because the result of the down selection process clearly indicated that the sodium receiver alternative was the preferred technology from a benefit and cost standpoint, and the process yielded strong consensus from the team. In the opinion of the facilitator, the answer is "No." Six key reasons were noted in support of the decision:

1. The team used the leading methodology and technology for group decision-making;
2. The team had functional diversity within its TAC and Leadership Team;
3. The benefit and risk hierarchies were developed in a highly collaborative manner over a six-month period, enabling the team to fully understand the definitions of the criteria and sub-criteria;
4. The team utilized a standard set of assumptions and performed a considerable amount of data analysis before applying their judgment in the scoring session;
5. Cost was treated as an independent variable, and the team was able to clearly and accurately consider benefit vs. cost vs. risk tradeoffs.

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REFERENCES

Additional information available in the project final report at:
C. Turchi, S. Gage, J. Martinek, et al. "CSP Gen3: Liquid-Phase Pathway to SunShot," NREL/TP-5700-79323, National Renewable Energy Laboratory, Golden, CO, July 2021, https://www.nrel.gov/docs/fy21osti/79323.pdf.

1. "Program on Technology Innovation," Vanderbilt University, Nashville, TN, Jul. 2015.
2. K. N. Papamichail and S. French, "25 Years of MCDA in nuclear emergency management," *IMA Journal of Management Mathematics*, vol. 24, no. 4, pp. 481–503, 2013.
3. E. Triantaphyllou and S. H. Mann, "Using the analytic hierarchy process for decision making in engineering applications: some challenges," *International Journal of Industrial Engineering: Applications and Practice*, vol. 2, no. 1, pp. 35–44, 1995.
4. B. Akash, R. Mamlook, and M. Mohsen, "Multi-Criteria Selection of Electric Power Plants Using Analytical Hierarchy Process," Electric Power Systems Research, 1999.
5. J. L. C. Meza, M. B. Yildirim, and A. S. M. Masud, "A Multiobjective Evolutionary Programming Algorithm and Its Applications to Power Generation Expansion Planning," *IEEE Transactions*, vol. 39, no. 5, pp. 1086–1096, 2009.

6. T. L. Saaty, “How to make a decision: the analytic hierarchy process,” *European Journal of Operations Research*, vol. 48, pp. 9–26, 1990.
7. T. L. Saaty, “Decision making with the analytic hierarchy process,” *Int. J. Services Sciences*, vol. 1, no. 1, pp. 83–98, 2008.
8. J. S. Dyer, “Remarks on the Analytic Hierarchy Process,” *Management Science*, vol. 36, no. 3, pp. 249–258, 1990.
9. S. P. Sindhu, V. Nehra, and S. Luthra, “Recognition and Prioritization of Challenges in Growth of Solar Energy using Analytical Hierarchy Process: Indian Outlook,” *Energy*, vol. 100, pp. 332–348, 2016.
10. P. O. Kim, K. J. Lee, and B. W. Lee, “Selection of an optimal nuclear fuel cycle scenario by goal programming and the analytic hierarchy process,” *Annals of Nuclear Energy*, vol. 26, no. 5, pp. 449–460, 1999.
11. C.-O. Shin, S. H. Yoo, and S.-J. Kwak, “Applying the analytic hierarchy process to evaluation of the national nuclear R&D projects: The case of Korea,” *Progress in Nuclear Energy*, vol. 49, no. 5, pp. 375–384, 2007.
12. “Analytic Hierarchy Process (AHP),” *American Society for Quality (ASQ)*. http://asq.org/service/body-of-knowledge/tools-analytic-hierarchy-process.